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Limitations to human livelihoods and well-being in the context of climate change

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Contents

Abstract

Limitations to human livelihoods remain a problem in many regions of the world and climate change impacts are expected to exacerbate such limitations in the future. While a large body of research is devoted to the topic of human well-being, human needs and livelihood requirements, a systematic and applicable framework to assess livelihood limitations in the context of climate change is so far unavailable. This thesis first develops an approach to assess *Adequate Human livelihood conditions for wEll-being And Development (AHEAD)* on a global scale. The approach allows to relate sectoral impacts of climate change to an integrated measure of livelihood limitations, taking into account important determinants of the society as well as the environment. Two additional detailed sectoral studies on water availability and human health show how local and regional studies of specific livelihood aspects can complement generic, global assessments and provide an overall indication of the nature, severity and spatial distribution of limitations to human livelihoods.

On the basis of a qualitative literature review to derive determinants of adequate livelihoods, a total of 16 elements are identified allowing to assess the fulfilment of AHEAD. Two methodological approaches to operationalise AHEAD elements are presented, each contributing to improve our understanding of livelihood limitations. The first implementation to assess AHEAD fulfilment uses a systems thinking approach, which outlines the degree of activity and connectivity of each element and reveals how climate change impacts may propagate through the system and lead to indirect effects on many system components. The second approach uses the method of fuzzy logic to assess the global state of livelihood conditions, analysing in which regions of the world changes in water availability affect AHEAD in the coming decades. The subsequent sub-national studies serve to assess limitations to the sectors water and human health in detail, again employing a fuzzy logic methodology.

The results of the system thinking assessment show, that water as an element of AHEAD is one of the most active system components. Impacts of climate change on water may have strong indirect effects on livelihood adequacy. The potential impacts of changes in water availability are quantified in the second implementation of AHEAD, showing that water scarcity limits livelihood adequacy in many regions of the world. The utilisation of an ensemble of climate change and water models further allows to assess the relevance of model related uncertainty in this regard. As water availability plays a crucial role for the fulfilment of livelihood needs, the global assessment is complemented by a detailed analysis of the adequacy of water availability for relevant sectors. By taking into account sector-specific determinants, including aspects of water quality, infrastructure as well as detailed accounts of sectoral water resource needs, the approach allows to depict limitations in detail, also giving indications as to how water adequacy may be improved. Similarly, the analysis of heatwave impacts on human health provides a novel methodology to assess the multiple environmental and human influences which affect vulnerability and provides specific information on potential adaptation measures to reduce climate impacts.

The findings provide knowledge of limitations to human livelihoods at a new level detail and disaggregation. By identifying the most decisive limiting factors, applicable information on how to most effectively improve human livelihoods is generated.

Zusammenfassung

Nach wie vor sind in vielen Regionen der Welt Armut und unzulängliche Lebensbedingungen ein wichtiges Thema und es bestehen enge Verknüpfungen zwischen den vorherrschenden Lebensbedingungen und den Auswirkungen des Klimawandels. Bisher fehlt jedoch eine systematische und praktikable Methode, um Klimaauswirkungen quantitativ mit menschlichen Lebensbedingungen in Verbindung zu setzen. Diese Arbeit entwickelt zunächst einen Ansatz, der die Quantifizierung der Angemessenheit von Lebensbedingungen für Wohlbefinden und Entwicklung (Adequate Human livelihood conditions for wEll-being And Development (AHEAD)) auf globaler Ebene ermöglicht. Mit AHEAD können außdem sektorale Klimaauswirkungen direkt in Beziehung zu den Voraussetzungen für adäquate Lebensbedingungen gesetzt werden. Zwei weitere Studien befassen sich im Detail mit den Themen Wasserverfügbarkeit und menschlicher Gesundheit und zeigen auf, wie regionale und lokale Untersuchungen die Aussagekraft von allgemeinen, globalen Studien erweitern können.

Auf Basis einer Literaturanalyse werden zunächst 16 Elemente identifiziert, auf deren Grundlage sich Erfüllung von AHEAD abschätzen lässt. Zur Umsetzung und Quantifizierung der Elemente werden zwei Methoden vorgestellt, die jeweils wichtige Erkentnisse über Einschränkungen von Lebensbedingungen liefern können. Zunächst werden anhand eines Systemansatzes der Grad der Vernetztheit und der Aktivität der einzelnen Elemente dargestellt. Diese Methode ermöglicht die Analyse von Wirkungspfaden innerhalb des Systems und zeigt auf, inwieweit Veränderungen einer Systemkomponente indirekte Auswirkungen auf andere Elemente und das Gesamtsystem haben können. In der zweiten methodischen Umsetzung wird die globale Situation von AHEAD, auch im Bezug auf mögliche Klimaveränderungen, mit Hilfe eines Fuzzy Logic Ansatzes quantifiziert. In beiden globalen Analysen werden Anhand des Beispiels Wasser mögliche Auswirkungen des Klimawandels abgebildet. In ähnlichen Verfahren werden in den beiden folgenden Analysen auf der Basis von Fuzzy Logic sektor-spezifische Limitationen in den Bereichen Wasser und Gesundheit analysiert.

Die Ergebnisse des Systemansatzes zeigen, dass Wasser als Element von AHEAD eine besonders aktive Komponente des Systems ist, so dass durch Klimawandel bedingte Veränderungen starke Auswirkungen auf das Gesamtsystem zur Folge haben können. Die Quantifizierung von AHEAD im zweiten Ansatz zeigt, dass Wasserknappheit die Lebensbedingungen bereits heute in vielen Regionen limitiert und Auswirkungen des Klimawandels diese Limitierungen weiter verstärken. In der darauffolgenden detaillierten Analyse zum Thema Wasser werden Aspekte der Bereiche Quantität, Qualität und Infrastruktur integriert, die es erlauben, sektor-spezifische Einschränkungen, auch im Bezug auf Klimawandel, im Detail zu analysieren. Damit ermöglicht die Analyse auch die Ableitung von geeigneten Ansatzpunkten zur Verbesserung der Bedingungen. In einem ähnlichen Ansatz werden die vielfältigen sozio-ökonomischen und natürlichen Einflussfaktoren, die die Auswirkungen von Hitzestress auf die menschliche Gesundheit beeinflussen integriert, so dass die Ableitung relevanter Informationen zur Reduktion von Klimaauswirkungen auf das menschliche Wohlbefinden möglich wird. Eine Verbindung der vorgestellten Ansätze erlaubt es, Aussagen über die Art, die Intensität sowie die räumliche Ausprägung von aktuellen und zukünftigen Einschränkungen von Lebensbedingungen zu treffen.

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1
Introduction

1 Livelihoods conditions and human well-being: relationship to processes of global change

Inadequate livelihood conditions and unfulfilled human needs remain a major problem in many regions of the world, and further development is needed to reduce poverty and fulfil needs (Sachs and Mcarthur, 2005; UN, 2012; Nsiah-Gyabaah, 2009). Current development pathways towards improved livelihood conditions, however, are often unsustainable, leading to processes of environmental degradation, which also include long-term and large-scale effects (Foley et al., 2011; Rockström et al., 2009a; Griggs et al., 2013). Improvements in livelihoods are thus currently often bought at the cost of damaging the environment. A transition towards more sustainable patterns of development, increasing the adequacy of livelihoods while reducing negative effects of development, is urgently needed. For instance, the current high levels of greenhouse gas emissions from human activities, such as energy production, industrial production or mobility, change the composition of the atmosphere, leading to an increase in global mean temperature at unprecedented rates. Regional manifestations of climate change are expected to display large variations and it is likely that these changes will lead to severe adverse regional impacts (IPCC, 2012). Existing livelihood restrictions in this context may also reduce adaptive capacity to cope with climate impacts (Smit and Wandel, 2006) and further exacerbate negative effects.

Other damaging effects of development include the large-scale exploitation of resources, for example for agricultural and industrial production, which lead to the depletion of resources. Associated pollution additionally threatens ecosystem sustainability (Rockström et al., 2009a; Gleick and Palaniappan, 2010). While current development pathways increase well-being in the short term, this could turn to the contrary when critical limits of pollution and exploitation are reached, which is already the case in many regions of the world (Rockström et al., 2009b; Foley et al., 2011). The pressures induced by climate change, pollution and overexploitation often add on to the existing development deficiencies, leading to the emergence of deprivation hot-spots. Cumulative livelihood limitations in the context of global change have for example been suggested as a potential threat to societal stability and human security (Adger, 2010; Barnett and Adger, 2007; Barnett et al., 2010; O'Brien and Leichenko, 2005). Both, poverty and environmental degradation, as well as the interplay between them, top the list of the most urgent security threats identified by the High-level Panel on Threats, Challenges, and Change of the United Nations (UN, 2004).

Climate change is one of the most urgent environmental problems of our time (Rockström et al., 2009a) and knowledge of the causes and effects (IPCC, 2013; Hare et al., 2011) as well as possible management strategies, such as adaptation and mitigation (Meinshausen et al., 2009; Arnell et al., 2013; Adger et al., 2007) is rapidly increasing. Important advances have been made in the field of climate impact and vulnerability studies to increase knowledge of the potential consequences of climatic changes on important natural and societal sectors (Hare et al., 2011; Holsten and Kropp, 2012). The motivation behind climate impact assessments is the realization that impacts may diminish human well-being and reduce the adequacy of human livelihood conditions. However, impacts and vulnerability assessments are usually conducted with a sector-specific focus, employing sector-specific impact metrics. A common framework for the integration of such results with regard to their effects on human well-being and livelihoods has so far been unavailable. The results of a recent Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP), for example, analyse in detail the severity of potential biophysical impacts of climate change on life-supporting sectors (Warszawski et al., 2014). A synthesis of the multiple biophysical impacts identifies hot-spots of change, but recognises the need for additional analyses to assess the societal effects of such pressures (Piontek et al., 2013).

Figure 1.1 summarizes the main generalized linkages between human livelihoods and well-being, socio-economic development pathways as well as the negative consequences that such development may entail, if pursued unsustainably. The area shaded in grey depicts those aspects which are at the core of the analyses conducted in this theses.

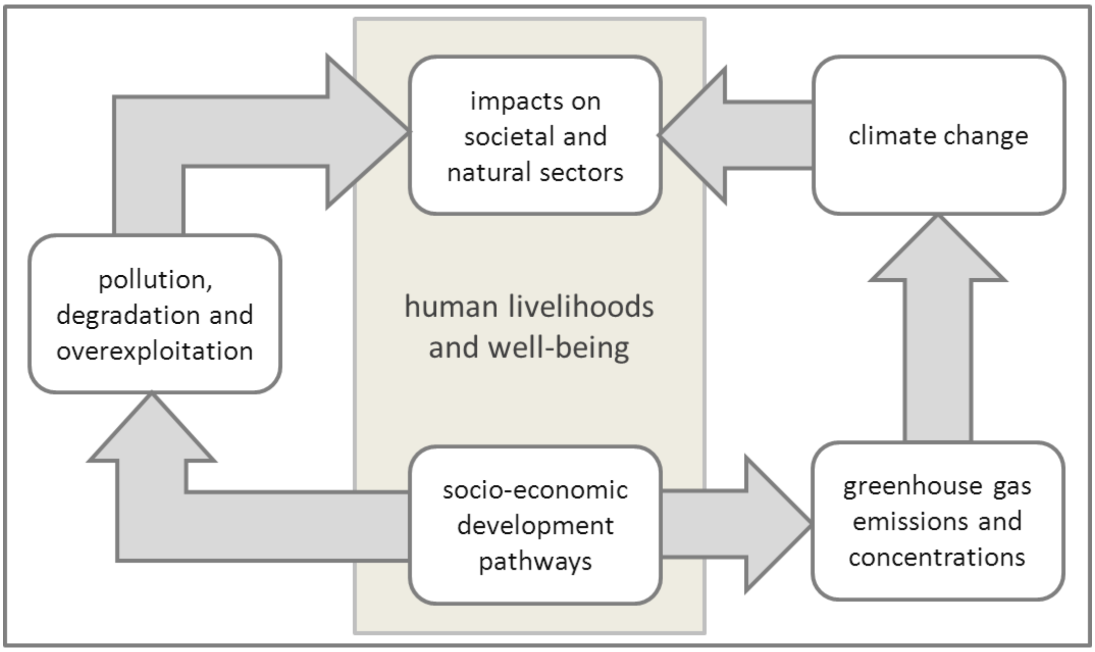

Figure 1.1: Overview of linkages between livelihoods and human well-being and global change processes and research

Livelihood conditions and human well-being as well as the impacts of climate change are determined by processes in both, the environmental and societal domains (Rasmussen and Arler, 2010). The importance of assessing processes at this interface of human and environmental systems, also in the context of climate change and sustainability, has often been noted (Folke, 2006; Madrid et al., 2013; Hummel et al., 2013; Oldfield and Barnosky, 2013). Nonetheless, assessments and models are often unsatisfactory and limited (Reid et al., 2010). Many open issues remain in the assessment of human-environmental systems, which include conceptual challenges, for example combining the different research philosophies of involved research disciplines (Newell et al., 2005). Additionally, there are methodological open issues, for instance the integration of explanatory factors at different temporal and spatial scales (Ostrom, 2009) or the reproduction of causal relationships between important system elements (Liu et al., 2007).

Water is one of the most essential goods contributing to adequate human livelihoods. Its availability is closely linked to both, the socio-economic development pathways as well as to climate change. Therefore, the topic provides an important starting point to address the multiple challenges encountered when carrying out assessments of livelihood limitations. Water availability is thus a common theme addressed in the analyses throughout this thesis. Water use is determined by prevailing consumption patterns and there is a trend towards more water intensive lifestyles across the world (Hoekstra and Chapagain, 2006). For instance, different dietary patterns have different water-intensities in their production (Rijsberman, 2006; Mekonnen and Hoekstra, 2010) and increasing prosperity and development across the world leads to shifting dietary patterns towards higher energy- and water-intensity (Pradhan et al., 2013). Climate change will likely alter temperatures and precipitation patterns, also resulting in changes of seasonal and temporal variations in physical water availability (Bates et al., 2008; IPCC, 2012). The additional changes in water use patterns coupled with population increases will likely lead to situations of water scarcity for human use, even if overall water resources remain constant or increase.

2 Measuring livelihood limitations: challenges and research gaps

Several research gaps and challenges need to be addressed in order to systematically explore the linkages between human livelihoods and climate change and to increase our understanding of the consequences, that changes in the biophysical life support systems may entail. First and foremost, this concerns the current lack of a systematic framework to describe and measure the requirements for adequate human livelihoods. Further, several conceptual and methodological challenges remain in assessments of human-environmental systems, which need to be taken into account in order to develop methods which can appropriately and meaningfully contribute to filling the remaining research gaps. Each of the following paragraphs outlines research gaps as well as challenges relevant to the objectives of this thesis. For each paragraph, a statement containing a main challenge is deduced, which we be addressed in detail in the analyses in this thesis. The first two main challenges are specifically in the focus of the main research questions of this thesis (Section 3 of this Chapter), while the third outlined challenge is implicitly addressed in each methodological implementation throughout the thesis. The final synthesis of the thesis (Chapter 6) elaborates in detail, how the results obtained in the individual analyses were able to contribute to filling the research gaps and addressing the challenges.

Describing and measuring livelihoods and well-being

A large body of research from many disciplines exists on the topics of livelihood and well-being. As a result, many different definitions of livelihood requirements have been proposed, which is a major challenge with regard to a clear description of the concept. This leads to the existence of homonyms where the same term is used to describe different concepts. The term 'well-being', for example, has been used in different disciplines to describe different things, including mental health (The WHOQOL Group, 1998) or life satisfaction (subjective well-being) (Peterson, 2012). These differences have been discussed in detail, see for example McMahon et al. (2010); de Chavez et al. (2005); Gasper (2004). Additionally, synonyms are used to describe overlapping or similar concepts. Synonyms for human well-being include terms such as quality of life (Cummins, 1996), livelihoods (Wisner et al., 2004) or human security (Gasper, 2005), which are often used interchangeably (Berenger and Verdier-Chouchane, 2007) (see also Alkire, 2002; Gough, 2003). Such conceptual issues of synonyms and homonyms have been identified as an important barrier in interdisciplinary research (Newell et al., 2005; Füssel, 2007).

To quantify limitations to livelihoods, the various approaches to assess and describe human livelihoods need to be consolidated into a common framework and translated into a measurable concept. For the purpose of this thesis, livelihoods are defined following Wisner et al. (2004), who see livelihoods as

> the command an individual, family, or other social group has over an income and/or bundles of resources that can be used or exchanged to satisfy its needs. This may involve information, cultural knowledge, social networks and legal rights as well as tools, land and other physical resources (Wisner et al., 2004, p.12).

According to Nsiah-Gyabaah (2009), fulfilled livelihoods can be seen as a prerequisite for human well-being, allowing for self-determined and forward-looking development decisions, which is also the approach used for the analyses within this thesis. Well-being, as defined here, has also been described as the counterpart of deprivation or poverty (D'Acci, 2011) and is closely linked to the term 'livelihoods'. The definition here relates to objective well-being, which is measurable through the access to tangible as well as intangible assets (fulfilled livelihood requirements) (D'Acci, 2011). Compared to this, the terms 'subjective well-being' or 'mental well-being' are related to individual happiness and positive mental health (Huppert and So, 2013), which is not in the scope and focus of this thesis. The various approaches which exist to describe requirements for fulfilled human livelihoods are also inhomogeneous with regard to the level of detail regarding the specified elements of livelihoods as well as the scale of assessment (e.g. individual well-being vs. national assessments).

Conceptual barriers originate not only from semantic inconsistencies, but also from the different disciplinary modes of thinking. A thorough understanding of interactions is hindered by methodological differences between the disciplines involved in human-environmental systems (Newell et al., 2005; Ostrom, 2009). Therefore, an essential first step towards a measurement of limitations to human livelihoods is a careful assessment of existing approaches. Semantic inconsistencies and disciplinary biases will be accounted for during this assessment. Summarising, the first main challenge that the thesis addresses is as follows:

> To quantify limitations to livelihoods, a consistent set of elements to describe and measure human livelihoods and well-being is urgently needed.

Explanatory factors and cause-and-effect relationships

Adequate livelihood conditions are determined by the availability of a range of tangible and intangible aspects from the societal and environmental domains. Processes which determine and affect human livelihood conditions therefore often play out at the human-environmental interface. Several important properties and challenges have to be taken into account when assessing such human-environmental systems, in order to generate meaningful representations of their functioning. To begin with, components of human-environmental systems are the often highly interconnected. Potential feedback effects, non-linearities or transition points may lead to unexpected consequences, deriving from changes in single system components (Liu et al., 2007). Some negative effects of climate change, for instance, only emerge in specific socio-economic or environmental settings, in which vulnerability-creating factors exist concomitantly. An initial detailed understanding of the main determinants and governing properties of the system under analysis is therefore an essential first step. This also includes the representation of causal relationships between determinants.

Additionally, explanatory factors often differ according to the scale of assessment and it is therefore pivotal to choose the adequate scale for the specific assessment context (Easterling and Polsky, 2004). Some questions may appropriately be addressed at global scales while others may require more detailed assessments of the local or regional situation. Generally, no assessment approach can claim universal applicability, but context-specific methodologies are needed to explain the variety of processes which govern human-environmental systems (Hukkinen, 2003).

Beside giving attention to the qualitative understanding of the system under analysis as an essential first step, the methodological implementation of causal relationships requires careful consideration. In this translation of the system description into a quantifiable representation, information regarding linkages is often lost, if simple aggregation methods are applied. The Human Development Index (HDI), for example, has been criticised in this regard, as the aggregation by averaging over all input factors implies substitutability between variables (Kovacevic, 2011). In the case of a disaggregated measure of livelihoods, however, not all aspects may be substitutable and aggregation procedures should be able to take this into account. To identify specific livelihood limitations and derive indications for efficient intervention points towards an improvement of these conditions, employed methods require the ability to maintain cause-and-effect chains and contextual relationships. This is the second main challenge which will be addressed.

> The translation of the multiple explanatory factors and cause-and-effect chains which govern human-environmental systems into meaningful and quantifiable representations requires methods, which allow retaining these causal relationships.

Bridging scales, combining data and addressing uncertainties

Several additional properties of human-environmental systems pose further challenges to the methodological implementation into measurable representations. One of these challenges is the fact, that the processes which govern the limitations to and impacts on livelihood conditions play out at different spatial as well as temporal scales (Ostrom, 2009; Scholz and Binder, 2004). The term 'scale' here may refer to both, the spatial and temporal dimensions (Sheppard and McMaster, 2008) and the integration of such differences of scale has been recognized as a major obstacle in human-environmental system analysis (Ostrom, 2009; Newell et al., 2005). Moreover, data required to represent aspects of the societal and environmental spheres is not only measured at different scales, but also involves different units and is collected using various methods (Parsons et al., 2011). Societal determinants of livelihoods for example, such as legal rights or political stability, are usually assessed within (national) administrative boundaries, while aspects such as water availability are assessed at catchment scale. Both aspects are relevant to describe human livelihoods, but differences in scale, resolution and measurement exist.

A further challenge comes into play when assessing the effect of climate change on livelihood conditions, as models and scenarios are subject to uncertainties. Uncertainties are an integral part of scientific analysis and cannot be fully eliminated and are generally understood as “an expression of the degree to which a value (e.g., the future state of the climate system) is unknown.” (IPCC, 2007a). Sources of uncertainty in climate change research are diverse, including data, the modelling process, underlying assumptions or appropriate scales of analysis (Schneider and Kuntz-Duriseti, 2002). Analyses of climate impacts rely on a range of input factors and as each component may have associated uncertainties, these build up along the modelling chain (cascading uncertainties) (Schneider and Kuntz-Duriseti, 2002). Especially different modelling assumptions as well as scenarios of potential future emission pathways lead to a large result range of potential future manifestations of climate change. This modelling spread may be substantial as the recent Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) has shown (Schewe et al., 2014; Warszawski et al., 2014). Such a result spread may render an interpretation of results rather difficult and modelling uncertainties have been blamed for causing inaction regarding climate change policies (see e.g. Lorenzoni et al., 2007). One important open question in this regard is how to suitably frame uncertainties in order to overcome some of these barriers (Smith and Stern, 2011). The last main challenge addressed in the thesis thus concerns important open questions in the methodological implementation of human-environmental system analysis:

> Methods for the assessment of livelihood limitations in the context of climate change require addressing differing temporal and spatial scales, differences in measurements and units as well as handling uncertainties associated with climate models and scenarios.

3 Research questions

The previous sections outlined the topical setting in which the analyses of this thesis are situated and summarized three important research gaps and challenges, which need to be addressed to assess limitations to human livelihoods in the context of climate change. To fill the gaps and provide ways forward in meeting the challenges, three specific research questions guide the analyses presented in the following chapters. Before formulating each research question, the context and major aim of each question will be summarized briefly.

As stated in Section 1 of this Chapter, the relevance of livelihood conditions and human well-being for climate impact research has been acknowledged (MEA, 2005; Foley et al., 2005; Barnett et al., 2010). However, a quantified representation of specific linkages is lacking due to the fact that a systematic consolidation of relevant dimensions and elements to describe livelihoods and well-being has so far been unavailable. The analyses conducted to answer Research Question I therefore aims at the identification of a consistent set of elements, consolidated from the multitude of existent approaches and theories from different disciplines. To overcome the interdisciplinary challenge regarding the semantic as well as conceptual differences between disciplines (Newell et al., 2005; Ostrom, 2009), a systematic, qualitative literature review is carried out (Petticrew and Roberts, 2006), providing a strong scientific basis on which to develop these dimensions. The first research question is therefore formulated as follows:

> **Research question I:** What are the main determinants and basic conditions needed for adequate livelihoods and human well-being?

Following the identification of relevant dimensions of human livelihood needs, the objective of Research Question II is to translate these dimensions into a measurable framework, in order to quantify potential limitations. To do so, a range of data from multiple sources and in different units need to be combined, which requires the application of suitable methods (Parsons et al., 2011). For the purpose of translating the elements of livelihoods into quantifiable representations, two methods are developed. The initially applied system thinking approach (Vester, 2007; Cole, 2006) focusses specifically on the relationships between elements and on their positions with regard to the whole system of livelihoods. In a second approach, a fuzzy logic algorithm (Zadeh, 1965; Kropp et al., 2001) is established to quantify the adequacy of the single elements as well as an aggregate measure of livelihoods and well-being. A quantifiable representation of livelihood elements offers the possibility of identifying specific limitations to livelihoods, providing indications on how to most effectively improve prevailing conditions. Furthermore, this way the assessment of climate impacts on human livelihoods and well-being within a common framework becomes feasible. The methodological implementation of a measure fo livelihoods is addressed in the second research question:

> **Research question II:** How can the main determinants of livelihoods and well-being be measured in a framework applicable in climate impact and sustainability research?

While the first two research questions are devoted to analysing and measuring livelihood conditions at global scale, mainly focussing on the first of the previously outlined challenges (Section 2), the third question addresses the issue of causal relationships and their methodological representation. The importance of accounting for causal relationships in human-environmental system assessments has been recognized (Liu et al., 2007), yet their implementation into quantified representations remains challenging. Especially the aggregation of the determinants of the system under analysis often leads to a loss of information with regard to the most influential factors for the overall result (Kovacevic, 2011). An initial, thorough understanding of the elements of the system as well as their interactions at the appropriate scale is an essential starting point to be able to provide an in-depth assessment of specific livelihood limitations. Methods are required, which allow to translate the conceptual understanding of governing cause-and-effect relationships into quantifiable representations. Such methods will further be referred to as *cause-and-effect-retaining methods*. By focussing on the development of cause-and-effect-retaining methods, the conducted analyses allow to clearly identify those factors, which are most decisive in limiting the adequacy of livelihoods. The analyses with regard to Research Question III are therefore devoted to developing such methods:

> **Research question III:** How can cause-and-effect retaining methodologies be developed, which allow for the identification of context specific limitations to livelihoods?

Each of the outlined research questions is an important contribution to determining where limitations to global livelihood conditions may lie and how these may be affected by climate change processes. The results attained with regard to RQ I through III are therefore the basis on which to address the overarching objective of assessing limitations to livelihoods and human well-being in the context of climate change.

3.1 Structure of the thesis

To answer the research questions, the thesis is structured into five chapters. Figure 1.2 provides a visual outline of the chapters of the thesis, showing their contributions to answering the three research question. Due to the close conceptual and topical linkages between the analyses, each chapter also contributes to addressing the other research questions. Chapters 2 and 3 are dedicated to analysing human well-being and livelihood conditions at a global scale and provide the main analyses towards answering the Research Questions I and II. Chapter 2 focusses on identifying generally valid determinants of human well-being and proposes a globally applicable framework. The chapter further addresses the measurement of the determinants of human well-being, which can be applied to analyse impacts of climate change on human well-being. The framework is further elaborated in Chapter 3, which presents a detailed analysis of impacts of changes in water availability on human livelihood conditions.

Globally applicable approaches are important to advance general understanding, however depending on the scale of analysis and the topic of interest, the relevant determinants as well as interrelationships may differ (Easterling and Polsky, 2004). Chapters 4 and 5 are therefore devoted to more specific analyses of topics highly relevant to human livelihoods, providing more detailed assessments for the sectors of water availability and human health, by developing sector-specific cause-and-affect retaining methods. In conjunction, the global and regional approaches can then give in-depth insights into livelihood limitations and provide important information on the specific nature of potential livelihood

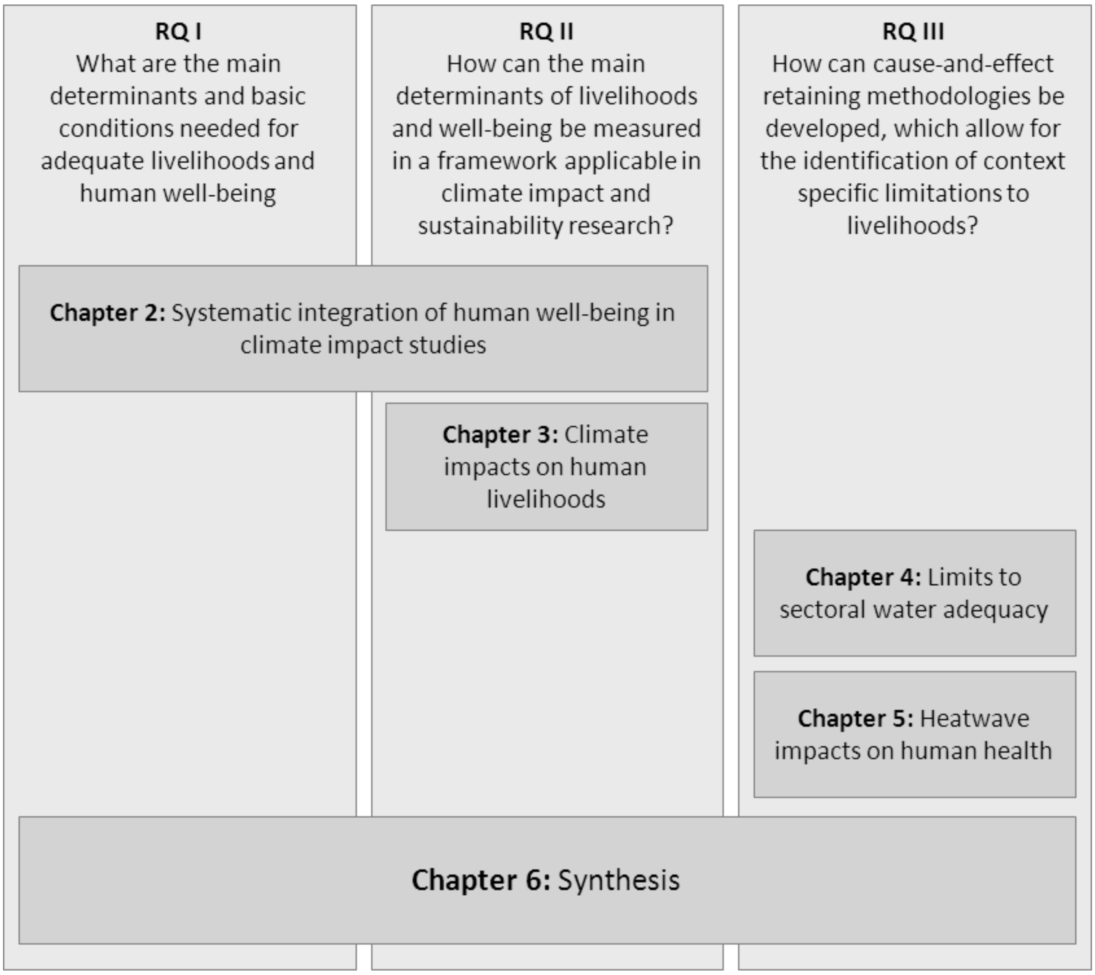

Figure 1.2: Visual outline of the structure of the thesis, showing the main contributions of individual chapters to answering the research questions and central objectives. Chapter titles are the short titles used in the individual chapters.

limitations. In this regard, Chapter 4 focusses on analysing the multiple social and natural determinants of adequate access to water resources, a central aspect of human livelihood needs and highly sensitive to climate change. Chapter 5 outlines and exemplifies an approach to measure climate impacts on human health. The results of the individual chapters are synthesised and critically discussed with regard to their contribution to the research questions in Chapter 6.

3.2 Individual Chapters

Chapters 2, 3, 4 and 5 have been prepared for publication in peer-reviewed journals and are presented in the style of journal articles. Due to methodological and topical similarities, some overlap between the contributions exists and each chapter has an individual introduction and discussion. The chapters have been published in peer-reviewed journals as follows:

Chapter 2:	A systematic approach to assess human well-being demonstrated for impacts of climate change. Lissner, Tabea K., Reusser, Dominik E., Lakes, Tobia, Kropp, Jürgen P. (2014) *Change and Adaptation in Socio-Ecological Systems.* DOI: 10.2478/cass-2014-0010.
Chapter 3:	Climate impacts on human livelihoods: where uncertainty matters in projections of water availability. Lissner, Tabea K., Reusser, Dominik E., Schewe, Jacob, Lakes, Tobia, Kropp, Jürgen P. (in press) *Earth System Dynamics.*
Chapter 4:	A management model determining regional limits and sectoral constraints for water usage. Lissner, Tabea K., Reusser, Dominik E., Lakes, Tobia, Sullivan, Caroline A., Kropp, Jürgen P. (in press) *Hydrology and Earth System Science.*
Chapter 5:	Towards sectoral and standardised vulnerability assessments: the example of heatwave impacts on human health. Lissner, Tabea K., Holsten, Anne, Walther, Carsten, Kropp, Jürgen P. (2012) *Climatic Change* 112(3-4), 687-708.

Two appendices are attached to the main body of the thesis, which contain supplementary information to Chapters 2 and 3 which is published in the respective journal along with the main articles.

Appendix I	Supplementary Material to: A systematic approach to assess human well-being demonstrated for impacts of climate change. Lissner, Tabea K., Reusser, Dominik E., Lakes, Tobia, Kropp, Jürgen P. (2014) *Change and Adaptation in Socio-Ecological Systems.* DOI: 10.2478/cass-2014-0010.
Appendix II	Supplementary Material to: Climate impacts on human livelihoods: where uncertainty matters in projections of water availability. Lissner, Tabea K., Reusser, Dominik E., Schewe, Jacob, Lakes, Tobia, Kropp, Jürgen P. (in press) *Earth System Dynamics.*

2

A systematic approach to assess human well-being demonstrated for impacts of climate change

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Abstract

Climate change impacts will affect many important societal sectors, with potential negative consequences for human well-being and livelihoods, however an integrated and systematic measure to assess the state of livelihood conditions in this context is not available. At the same time, human livelihoods and well-being are an important part of (social) sustainability. Yet, aspects of human needs and well-being within assessments of sustainability are criticised for being arbitrary and incomplete. This paper presents a systematic approach to assess Adequate Human livelihood conditions for wEll-being And Development (AHEAD) on a regional to global scale. Based on an interdisciplinary literature review, we first select a consistent set of elements that allow to describe and quantify well-being and livelihoods. In a second step, we analyze documented associations between the elements to outline climate impact pathways and indirect effects of changes in single system components, using an influence matrix. The novel approach provides an important first step to point towards climate change adaptation measures, which most effectively increase human well-being, while identifying potential unintended side-effects. Even though there are a some limitations to assessing well-being and livelihoods on a global scale, a consistent measure of AHEAD is of utmost importance for future sustainability and climate impact analyses.

1 Introduction

Human influences on the natural system are altering biophysical processes and humanity is facing substantial challenges, including climate change, pollution and degradation of critical ecosystem services Rockström et al. (2009b). A transition towards sustainability is urgently needed, including pathways towards reduced resource use, while enabling and increasing human well-being Haberl et al. (2011). While efforts to improve our understanding of sustainability to provide guidance on such transition pathways have been substantial, operable and integrative approaches to link human and environmental systems remain scarce.

The relevance of jointly addressing processes of the environmental and societal domains has often been noted Folke (2006); Madrid et al. (2013); Hummel et al. (2013); Oldfield and Barnosky (2013), however the integration of domains remains challenging. Sustainability is commonly analysed using a three-pillar approach, differentiating economic, environmental and social sustainability. While the integrative nature of sustainability studies is stressed, the focus of assessments is often on the environmental components and representations of the social aspects are much less elaborated Boström (2012); Cuthill (2010); Holden and Linnerud (2007). Social sustainability has been described as the satisfaction of an extended set of human needs Littig and Griessler (2005); Holtz et al. (2008) and "has to do with improving or maintaining the quality of life of people" Weingaertner and Moberg (2011). However, indicators to represent social aspects are often inconsistent Steurer and Hametner (2011) or seem arbitrary and motivated by political reasons, rather than scientific ones Littig and Griessler (2005); Murphy (2012).

Impacts of climate change on livelihood conditions and human well-being are determined by processes in both, the environmental and societal domains Rasmussen and Arler (2010), yet linkages remain insufficiently explored. On the one hand, development pathways, which are followed in order to improve livelihood conditions and increase human well-being, are often associated with emissions of greenhouse gases and are an underlying cause of climate change Reusser et al. (2013). Reductions in human welfare and prosperity are feared, if strong mitigation measures to tackle climate change are implemented Lorenzoni et al. (2007). On the other hand, manifestations of climate change through impacts on natural and societal sectors have direct and indirect effects on human well-being. Climate impact studies show that climate change may threaten important aspects of peoples' livelihoods and may have severe repercussions for our current lifestyles Schneider et al. (2007); O'Brien et al. (2004). In order to reduce negative consequences, strategies to adapt to existing and anticipated impacts can be developed. However, if such adaptation strategies are devised in an unsustainable manner, these can further exacerbate climate change and degradation, leading to maladaptation Barnett and O'Neill (2010).

Integrative assessment methods, which allow to assess the indirect effect of adaptation are thus important, in order to increase human well-being, while promoting sustainable development.

While the important position of well-being and human livelihoods within human-environmental systems is recognized, so far an integrative and systematic measure of livelihoods and well-being is unavailable. Many approaches exist which outline important constituents of fulfilled human livelihoods and provide information on the relevance of each aspect for attaining human well-being (see for example Alkire (2002)). However, existing approaches originate from different disciplines, leading to differing foci in the selection of components. Various definitions of the terms livelihoods, well-being and human needs exist, which often overlap or are used synonymously (see Section 2). In the remainder of the paper we use the term well-being as a representative of the concepts. Further, approaches remain conceptual and qualitative, making a systematic quantification difficult. Generally, interdisciplinary topics require the *integration* of knowledge from different disciplines, but should also result in the *formation* of new knowledge or approaches, applicable in several disciplines Lam et al. (2012). On the one hand, interdisciplinary topics need to be formalized in a way that is applicable and quantifiable. On the other hand, such a formalization needs to be sufficiently flexible to be adjusted to the various fields of application. In the case of human well-being and livelihoods, an additional challenge are the various inter-linkages that exist between determinants that constitute human well-being, as well as linkages to external processes, such as climate change.

We propose to address the topic using a systems thinking approach, which promotes the idea of seeing the parts of a system as a whole and focussing on processes and relationships between system parts Vester (2007). Work on the food-energy-water nexus, for example, underlines the importance of such an approach, especially in coupled human-environmental systems Hoff (2011); Bazilian et al. (2011). System thinking methods have been applied in various contexts of sustainability assessments, including settlement planning Coplák and Raksanyi (2003), urban regions Wiek and Binder (2005) and sustainable transport OECD (2000), but are novel in the context of addressing human well-being, where conceptual and qualitative approaches prevail and linkages to processes in the environmental domain are usually not included. Existing approaches linking indicators of human well-being to processes of global change and sustainability often fall short in (I) substantially defining components of human well-being and (II) translating existing causalities into an integrated mathematical representation. The aim of the present paper is thus to develop an approach to assess the conditions for Adequate Human livelihood conditions for wEll-being And Development (AHEAD) by a consistent set of elements, which allow to relate processes of the environmental domain to human well-being. We focus on the systematic identification of elements and explore the associations and inter-linkages between them, thus contributing both to the integration as well as the formation of inter-disciplinary research. We exemplify how the AHEAD approach can contribute to understanding the impacts of climate change on well-being. The AHEAD approach can address a range of scales from global to local, however it does not take into account individual aspects of human well-being.

As a first step, we identify those (measurable) elements, which constitute essential requirements for AHEAD conditions (Section 2). We base the analysis on a comprehensive literature review, to derive scientifically valid determinants of AHEAD. We then look in detail on inter-linkages and relationships between the identified elements, again based on scientific findings, using a systems thinking approach (Section 3). The paper outlines how such an approach can be developed on a global scale and outlines generally valid elements, inter-linkages and potential dynamics. Elements and inter-linkages are presented in generic way, providing the basis for a first consistent formalization and quantification of the concept. To underline the importance of viewing AHEAD as an interconnected system and to look at the linkages between elements, we discuss selected examples of climate change impacts (Section 3.2). We critically discuss the results in Section 4 and summarize the main findings in a brief conclusion (Section 5).

2 Identifying elements of AHEAD

On the basis of a range of available approaches to measure human well-being, needs and livelihoods, we identify essential requirements for AHEAD. For the purpose of a generally applicable framework, the elements should be globally valid, regardless of cultural differences and rooted in scientific findings. Following the definition of Wisner et al. (2004) Wisner et al. (2004), AHEAD describes access to "an income and/or bundles of resources that can be used or exchanged to satisfy needs. This may involve information, cultural knowledge, social networks and legal rights as well as tools, land or other physical resources", thus representing an extended set of needs required for human well-being and social sustainability Littig and Griessler (2005).

To identify those approaches relevant to defining elements of AHEAD, we perform a qualitative literature review Petticrew and Roberts (2006). As we aim to identify a set of operable dimensions, we look for approaches that specifically list elements which contribute to AHEAD. Using combinations of the initial search terms 'human', 'well-being, 'needs', 'livelihoods' and searching title and abstract, we screen the results according to the following criteria: (1) human-centered (explicit focus on human well-being) (2) global applicability (3) transferability (4) explicit multi-dimensionality and (5) plausible foundation and accessible documentation.

Our initial keyword search returned over 900 results in the database of www.scirus.com. The results originate from a variety of disciplines. Hence, significant differences in terms of framing, tangibility and applicability exist. A very important aspect becoming apparent when screening the results is the fact that terminology is not straightforward: on the one hand, the same term is used to describe different things (homonyms) (see e.g. for the term well-being de Chavez et al. (2005); McMahon et al. (2010)). On the other hand, many terms exist to describe similar and overlapping concepts (synonyms), e.g. quality of life Cummins (1996), well-being Gasper (2004), livelihoods Wisner et al. (2004) or human security Gasper (2005), which are often used interchangeably Berenger and Verdier-Chouchane (2007) (see also Gasper (2005); Alkire (2002); Gough (2003). The initial keyword search was thus extended to a forward and backward search, screening the references of the identified important approaches in order to detect additional approaches, which may not be covered through the applied keywords.

After screening the initial results, as well as the additional approaches from the forward/backward search according to criteria 1 through 5, a total of 11 approaches could be identified, on which a measure of AHEAD can be based (detailed descriptions in Table A-I.1, Appendix I), namely Maslow's Theory of Human Motivation Maslow (1943), the Basic Human Needs Approach, McHale and McHale (1979); Doyal and Gough (1984); Weigel (1986), Human Scale Development Max-Neef (1992); Cruz et al. (2009) the Capability Approach Sen (1985); Anand et al. (2008); Gasper (2007); Nussbaum (2000), Human Security Gasper (2005); UNDP (1994); King and Murray (2001), Sustainable Livelihoods Scoones (1998); Chambers and Conway (1991), Quality of Life (QoL) Cummins (1996); Costanza et al. (2007), Subjective Well-Being (SWB) (Diener et al. (1999), cited in Alkire (2002)), the Millennium Ecosystem Assessment MEA (2005), Dimensions of Poverty Narayan et al. (2000) and the Measurement of Economic Performance and Social Progress Stiglitz et al. (2009). Many articles are concerned with describing and defining human well-being and livelihoods, however only few specifically outline and list relevant elements and determinants, which was the main restriction on the number of approaches directly suitable for the analysis (criterion 4: explicit multi-dimensionality). Therefore not all important contributions have been directly included to define dimensions of AHEAD, but after the comprehensive review it appears that all important aspects are covered through the sample. Several studies which are relevant to the topic, but are not applicable for the analysis, as they do not fit the five criteria introduced above, support the identified elements relevant to measure AHEAD (e.g. O'Riordan (2013); Littig and Griessler (2005); Raworth (2012)).

The 11 identified approaches to define elements of human well-being and livelihood requirements differ in terms of scope as well as terminology. However, each approach provides a specific list of elements relevant to human well-being, along with descriptions of the meaning and purpose of each element. This provides the basis on which to compare approaches and identify synonyms which are used to describe the elements in each approach. Some elements are included consistently in the majority of approaches, e.g. there is agreement on the need for subsistence, including elements such as water, food and air or the need to be healthy and have access to health care. Societal aspects, such as participation or social protection are also referred to in the majority of approaches, however here the framing and the definitions diverge more. We grouped equivalent and similar elements of well-being identified in the samples according to the descriptions in the corresponding literature. From this grouping, nine key elements emerge (Figure 2.1, see also Table A.I-1 and A.I-2 (supplementary) for detailed descriptions).

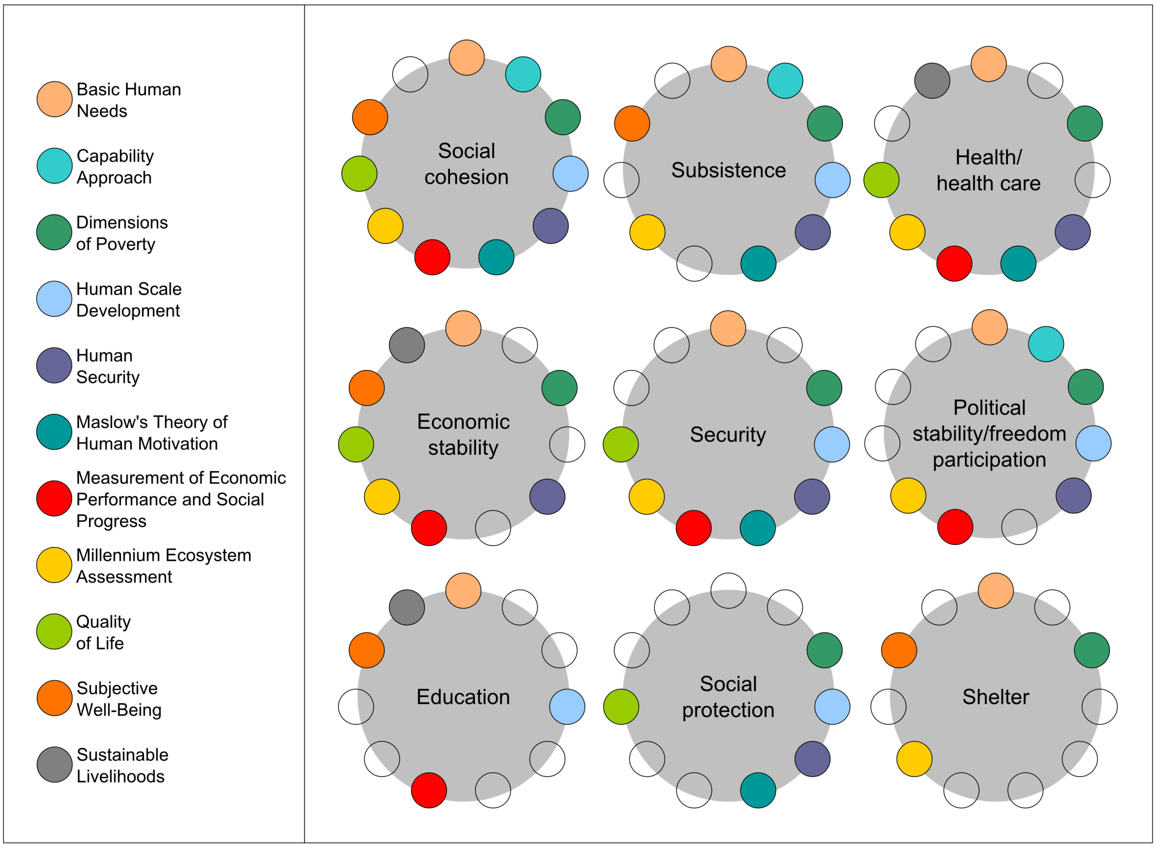

Figure 2.1: Key elements of requirements for human well-being as identified from relevant literature, sorted by coverage from the approaches. Colored bubbles depict, which approach identifies the respective element. The alphabetical order of the approaches (left) is identical to the order of the bubbles in clockwise direction, starting at 12 o'clock.

Of the nine groups of elements, social cohesion is most consistently included in the 11 selected approaches (10 out of 11). Further, the aspects of subsistence, health/health care, economic stability, security (all 8 out of 11) and political stability/freedom/participation (7 out of 11) are clearly important. The elements of social protection, education (5) and shelter (4) are less consistently named in the approaches, however, they are often mentioned implicitly, e.g. through ‘material living standards’ Stiglitz et al. (2009). Those aspects which clearly refer to individual aspects of human well-being (e.g. family, romantic relationships) are not included, as these would require a different scale of analysis. For individual well-being, these aspects play a critical role. To depict the general conditions and resources, both tangible and intangible, which provide a basis on which well-being can be attained, individual factors cannot be accounted for (for a list of all aspects from all approaches see Table A.I-1, Appendix I).

To achieve measurability, some of the key elements shown in Figure 2.1 have to be further differentiated. Especially the aspects of subsistence have to be assessed separately. We therefore distinguish water availability, water quality, calorie availability and air quality. Further, we distinguish political stability from participation. We also include three additional elements, which are not directly mentioned in any approach, but are of increasing importance in a globalized world, namely energy availability Pachauri (2004); Diffenbaugh (2012), communication Horner et al. (2010) as well as mobility Bradbury (2006). In total, 16 measurable elements of AHEAD emerge from the analysis. Table A.I-2 (Appendix I) gives further detailed support for identified elements for AHEAD, underlining their relevance as well as the respective literature sources.

While income is sometimes included as a separate requirement, for our approach we draw on findings from research on the relationship of subjective well-being and income, which indicate that wealth contributes to well-being and happiness up to where basic needs are met, but no strong direct correlation is apparent Diener et al. (1999); Diener and Biswas-Diener (2002); Easterlin et al. (2010). That is also reflected in the approach to the Human Development Index (HDI), for example, where GDP is included at log-scale Klugman et al. (2011). The importance of access to basic material goods within AHEAD is covered through the element of economic stability as well as the availability of essential resources (e.g. food, water) and infrastructure (e.g. shelter). Several elements may however have a dimension of affordability, as monetary resources may be used/needed to access them Sullivan (2002); Kruyt et al. (2009).

3 Relationships between the elements of AHEAD

While the identification of AHEAD elements in itself is important and each aspect is an essential factor for adequate living conditions, the elements are also highly interconnected and a holistic view gives important insights into the overall system of AHEAD conditions. We therefore investigate the relationships between the identified elements, using a system thinking approach Vester (2007); Cole (2006); Ninck et al. (2001). Such an approach can increase the understanding of processes within a system and show how external effects propagate through the system, as isolated assessments of single processes can ignore important feedbacks or secondary impacts. The use of an influence matrix, as proposed by Vester (2007) Vester (2007), requires detailed knowledge of the relevant system components and general relationships between variables (elements). We perform an additional literature search to find sufficient scientific evidence for the directed relationships between elements. The scale and scope of the present exemplification of the approach only allow for connections, which are generally valid on a global scale and for which scientific evidence could be found. Other association may exist at different spatial scales or may not have been documented in the literature. In the AHEAD approach, the system is characterized by a definite set of elements that are interconnected within a defined boundary. As we show in Section 3.2, external effects may impact the system state, but are not considered in the initial assessment of system associations and interconnections.

3.1 Identification of associations and linkages

The system boundaries of AHEAD are defined, so that all variables are part of the system, while outside effects are initially not considered. The question we are addressing is whether conditions are adequate for human well-being and livelihoods. Clearly, AHEAD is nested within other systems, and important processes come from the ecological and the political environment. According to the definition of the system boundary, activity and connectivity of outside factors are initially not considered and only direct relationships are included. The system is first formalized within the defined boundaries, then outside effects on the system are assessed. Using the influence matrix, the existence of a relationship between each element is denoted. For the purpose of an exemplification with generally valid relationships, we use two classes with $0 =$ no documented relationship and $1 =$ documented relationship, drawing on scientifically rooted, general findings on existing relationships. In regional to local applications of the approach, context-specific intensities and graduations of the relationships could further be differentiated, using expert knowledge or regionally specific assessments. The influence matrix is a square matrix M_{ij}, containing the system variables 1 to n in identical order in rows (i) and columns (j), in which identified relationships are denoted. Using this matrix, it becomes possible to rank the system components according to their activity and connectivity within the system.

$$AS = \sum_{i=1}^{n} M_{ij} \tag{2.1}$$

$$PS = \sum_{j=1}^{n} M_{ij} \tag{2.2}$$

From the row sums AS (active sums) (Equation 2.1) and column sums PS (passive sums) (Equation 2.2), the degree of connectivity P (Equation 2.3) as well as the degree of activity Q (Equation 2.4) of all components can be calculated.

$$P = AS * PS \qquad (2.3) \qquad\qquad Q = AS/PS \qquad (2.4)$$

The connectivity P provides a measure of interconnectedness of the system components: higher values stand for a high degree of interconnection of the respective variable into the system, while variables with low connectivity P are least relevant for the overall system. The degree of activity Q gives important insights into the properties and position of each variable within the system. Active components (Q>1) influence many other system components, but are influenced only by few elements. Opposed to this, passive components (Q<1) have a weaker influence on other system components, but may be heavily influenced Ninck et al. (2001); Cole (2006). Identified linkages are shown in the influence matrix in Figure 2.2 (for detailed explanations and literature sources for the documented linkages see Table A.I-3, Appendix I).

Influence of ↓on →		WA	WQ	CA	AQ	EA	SH	HCI	SP	PS	ES	SoP	SC	EDU	PAR	COM	MOB	AS	P
water availability	WA		1	1	0	1	0	0	0	1	1	0	0	1	0	0	0	6	12
water quality	WQ	1		0	0	1	0	0	0	0	0	0	0	0	0	0	0	2	4
calorie availability	CA	0	0		0	0	0	0	0	1	0	0	0	1	0	0	0	2	12
air quality	AQ	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0
energy availability	EA	1	1	1	1		0	1	0	0	0	1	0	1	0	1	1	9	18
shelter	SH	0	0	0	0	0		0	0	0	0	1	0	0	0	0	0	1	0
health care infrastructure	HCI	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0
social protection	SP	0	0	0	0	0	0	0		0	0	1	1	1	0	0	0	3	3
political stability	PS	0	0	1	0	0	0	0	0		0	1	0	0	0	0	0	2	10
economic stability	ES	0	0	1	0	0	0	0	0	0		0	0	0	0	0	0	1	3
security of person	SoP	0	0	0	0	0	0	0	0	1	0		0	0	0	0	1	2	10
social cohesion	SC	0	0	0	0	0	0	0	1	1	1	1		0	0	0	0	4	8
education	EDU	0	0	0	0	0	0	0	0	0	1	0	0		1	0	0	2	12
participation	PAR	0	0	0	0	0	0	0	0	1	0	0	0	0		0	0	1	2
communication	COM	0	0	0	0	0	0	0	0	0	0	0	1	0	1		0	2	2
mobility	MOB	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0		2	4
PS		2	2	4	1	2	0	2	1	5	3	5	3	4	2	1	2		
Q		3.00	1.00	0.80	0.00	4.50	0.00	0.00	3.00	0.40	0.33	0.40	2.00	0.75	0.50	0.50	1.00		

Figure 2.2: Influence Matrix of the AHEAD system. Based on available scientific evidence (Table A.I-2, Appendix I), valid relationships between elements are denoted with the number 1. PS and AS represent the passive and active scores of elements, Q represents their degree of activity and P represent their degree of connectivity.

From the determined inter-linkages, the activity measures P (Equation 2.3) and connectivity measures Q (Equation 2.4) are calculated. Indirect connections, where changes are effected through an intermediate element, are not accounted for with additional linkages within the matrix. Results denoted in the influence matrix can be visualized in an influence diagram (Figure 2.3), with the degree of activity Q denoted on the x-axis and the degree of connectivity P denoted on the y-axis. Four main zones can be differentiated within the plot, according to the activity and connectivity of elements (Z1 to Z4). These groups provide a first indication of the each element's position within the system, relative to all other system components. With regard to the degree of activity, the zones differentiate active and passive elements (Q >/<1). The identification of highly connected elements is based on the average connectivity of all elements. In the case of the present system of AHEAD the value of 6.25. Elements in the lower left corner (Z1) of the plot are the least active and least connected. Elements in the upper left corner (Z2) describe those elements, which are strongly influenced by other elements of the system, however they have little influence themselves. These variables present good indicators of the state of the system. Compared to that, elements in the lower right corner of the plot (Z3) strongly influence the overall state of the system, but are less affected by influences of other parts. Elements within this zone can thus point to good intervention points, as investments in the improvement of those elements can most actively have positive influences on other parts. The top right corner (Z4) is most active as well as connected within the system. Elements within this zone are both influenced by other variables, and in turn also effect stronger influences on other elements. They can lead to strong feedback effects, but also may have most leverage for effective interventions.

Of the 16 elements of AHEAD, five elements actively influence other components within the AHEAD system (Z3/Z4), while 9 elements are passive within the system (three of those are omitted from the plot, as both Q and P have a value of 0). The elements water quality and mobility have a Q-value of 1 and are thus neither passive, nor active. In terms of connectivity, seven elements are highly connected, while 9 have low to zero connectivity. Of the passive elements, five also have a low connectivity are thus less relevant from a systems perspective. The other five passive elements are found in Z2 and therefore may provide good indicator variables to describe and monitor the state of the system. Such elements are dependent on other parts of the system and subject to feedbacks from changes in other elements. Security of person, for example results from stable and secure situations in other system parts. The two active elements social protection and communication in Z3 are not highly connected, thus providing potential efficient and controllable intervention points. Changes in these elements may have strong effects on the rest of the system, but are less influenced by the system components themselves. Such elements are highly relevant for the system in terms of their potential to significantly change the overall system state and low connectivity does not refer to the importance of an element within the system. The results of our analysis places the elements energy availability, water availability and social cohesion into Z4, which are also amongst those elements recognized as most essential for human well-being in the literature.

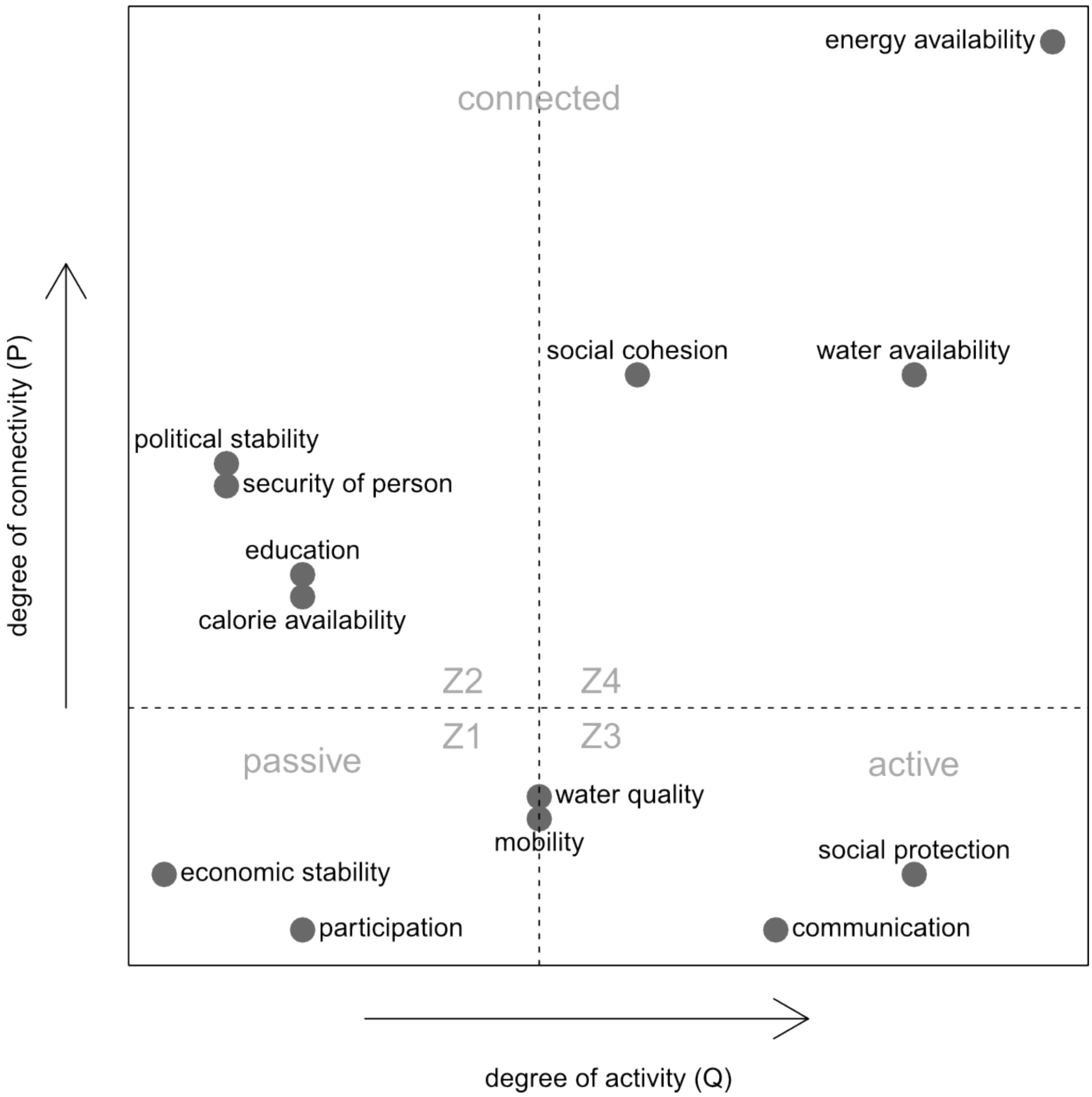

Figure 2.3: Influence diagram of activity and connectivity of the elements of AHEAD. Elements with Q=0 and P=0 are omitted (air quality, health care, shelter). For visibility, the elements 'political stability'-'security of person' as well as 'water quality'-'mobility' have been moved apart slightly, but actually have identical positions. Since the plot provides an overview of the positions of element relative to all other system components, there are no units given for the axis. Values correspond to those given in Table 2.1.

3.2 Impact pathways of change

The influence diagram (Figure 2.3) gives important insights into the degree of integration of each element. Further insight can be gained by looking in more detail into the properties of the relationships. Causal loop diagrams visualize the direction and types of the connections and can help in identifying impact pathways or possible feedback effects. To further illustrate the relevance of a systems thinking approach for AHEAD, we show how changes in single elements can propagate through the system and have indirect effects on other system components. Several elements are directly sensitive to climate change impacts. These elements are also amongst those, which are most closely related to environmental and economic sustainability and provide obvious linkage points between the pillars of sustainability. Water availability, for example, is especially at risk of adverse effects of climate change and is projected to change in the future Bates et al. (2008), as precipitation patterns and temperatures change. At the same time, water pollution is one of the most pressing environmental problems, which reduces resource availability for human use Vörösmarty et al. (2010a). Energy as the most active and connected element within the system, is core challenge of sustainable development: energy availability is critical for general development and as an input for a range of human activities and needs, but also contributes actively to environmental degradation and pollution, as well as resource use Rao et al. (2013). It is also an essential income generating factor and contributed to economic prosperity. At the same time, energy availability is both directly and indirectly affected by climate change, in terms of production as well as consumption Mideksa and Kallbekken (2010).

A integrated view of the system properties can illustrate how impacts on single components may propagate through the system and have secondary effects.Using the example of climate change and its effects on water availability, we outline potential impact pathways and their relevance for AHEAD, visualized in Figure 2.4.

Water availability directly influences energy production, as the latter relies on water for cooling, growing biomass for energy and water for hydro-power De Wever (2010). Reduced water availability can thus reduce energy availability through multiple pathways. Reliable access to energy can increase time for learning after dark Ranganathan and Ramanayya (1998) and reduce time for the collection of fuel wood Kanagawa and Nakata (2007); Practical Action (2013) and can increase education. Sufficient water availability can also directly influence education, as time is freed to attend school instead of collecting water resources Larson et al. (2006). The link between water availability and education is further enhanced through the availability of sufficient calories: agriculture and food production critically depend on water availability and availability of food can affect learning capacity and school attendance Brown (2002); Behrman (1996). In turn, basic education is a prerequisite to access important services and to contribute to societal stability Lutz and

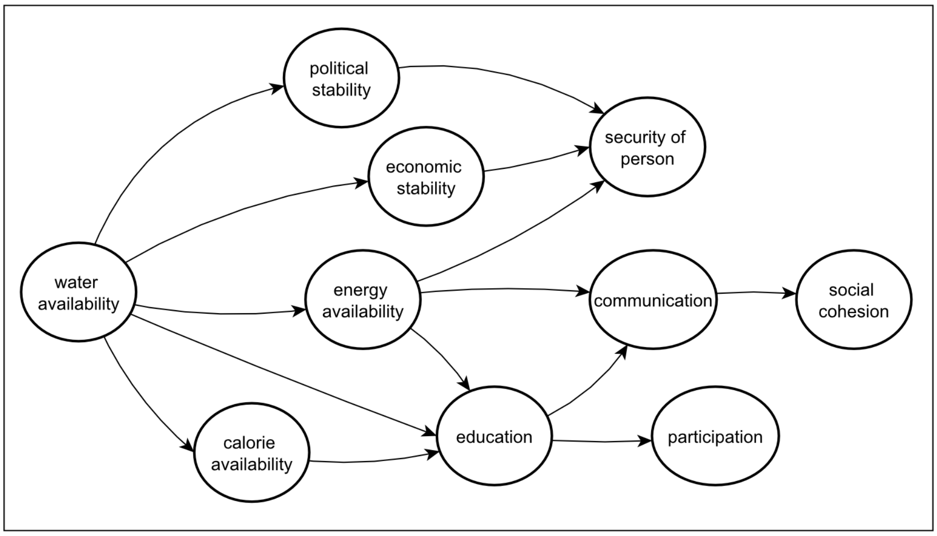

Figure 2.4: Exemplary pathway of impacts of changes in water availability on selected elements of AHEAD.

Samir (2011). For example, higher levels of education seem to increase likelihood for voting and other ways of civic participation and understanding seems to be key to be able to access existing channels of communication Milligan et al. (2004). Education enhances job skills, or the ability to acquire them, and thus secures better economic positions to ensure (personal) economic stability. On a higher level, better educated personnel will ensure economic reliability and availability of skilled workers to keep productivity up Buechtemann and Soloff (1994). There are indications that water scarcity directly influences the potential for conflicts and political stability Levy et al. (2005). However, this relationship is a topic of scientific discussion and cooperative water management is more frequent than (violent) conflict Scheffran and Battaglini (2010). Adequate access to sufficient water reduces time spent to acquire water and generally raise health status, so more time can be spent on generating household income and ensure economic stability Meeks (2012); Larson et al. (2006). A lack of economic and political stability can increase the likelihood of conflicts and thus reduces personal security WHO (2002b,a). Impacts on personal security can further derive from reduced energy availability, as the availability of electric street lights after dark can significantly improve security, especially of women Practical Action (2013). In this chain of processes, changes in water availability can thus have far reaching and potentially unexpected indirect impacts on single AHEAD elements and the overall system.

4 Discussion

A systematic approach to integrate human well-being into assessments is of high importance, however, existing concepts and approaches are currently not in an appropriate form for application in sustainability and climate change research. Disciplinary assessments of human well-being requirements are mostly based on only one theory, and topical foci or political reasons guide their definition Kovacevic (2011); Littig and Griessler (2005). Integrating knowledge from a range of disciplines, we show that commonalities between approaches can be identified and that the consolidation and aggregation of approaches from different disciplines is possible. We identify the core elements and translate them into measurable components to represent human well-being and needs for sustainability in an operable and consistent way.

While the single components of the proposed framework all provide essential resources for human welfare separately, processes and associations between system components prove to be important for the assessment of AHEAD conditions. Based on scientific evidence, we are able to show how the system components are interrelated. The system view allows identifying impact pathways and can thus provide important insights for climate change and sustainability science, by formalizing the process pathways and making visible indirect effects and interactions.

The analysis of a system by means of an influence matrix allows to point towards properties of the system components, which are relevant for the policy process. Policy options in general are often constrained by limited resources, thus efficient and high impact measures and actions which maximize human well-being and development should be favored. At the same time, knowledge of possible side-effects or feedbacks is important to avoid unintended outcomes. The degree of connectedness and activity of the system components can give such insights Ninck et al. (2001); Cole (2006). Social cohesion, for example, has been shown to have an important contribution to reducing the fragility of nation states Marc et al. (2013) and is also associated to a significantly higher health status of the community Stansfeld (2009). In our results, social cohesion is identified as a highly active element of AHEAD. It is also most consistently included as an important element of human well-being and needs.

The four zones in Figure 2.3 can be differentiated and especially elements in Z2 through Z4 can become relevant in a decision-making context. Elements in Z2 are not very active within the system, however, they are highly connected and are affected by changes in other elements. These elements can be helpful as indicators of the system state, as changes in the overall system are usually reflected here. Our results place the elements security of person and political stability in Z3, for example. Both have been found to diminish as a consequence of inadequate societal, economic and political realities Rotberg

(2003). They thus reflect the fact, that living conditions are declining. Directly investing in either of these elements, however, has little consequence for the system, as feedbacks from other elements will quickly dampen investments made. Elements in Z3, on the other hand, are little affected by system components, but can have a strong leverage effect, as they are actively influencing other elements and investments are dampened less through influence from other system elements. The two most active and connected elements within the framework, water availability and energy availability (both in Z4), are central to the challenge of a transition towards sustainability and also directly sensitive to climate change. Elements in Z4 are intensively interacting with system parts, and active interventions at these points often have strong effects, but feedbacks have to be expected. This is important information for policy-makers, for example, as potential side-effects can be taken into account if such properties are known.

In the case of water availability and use, for example, this is well reflected in the extensive body of research devoted to integrated water resources management (IWRM), which has the purpose of modeling many of these interactions. When reacting to the impacts of climate change on these sectors, for example, an integrated system view can make visible some of the potential pathways within AHEAD and reduce unintended consequences of adaptation interventions. The fact that energy, water and also calorie availability are not only essential human subsistence needs, but are also strongly interconnected is well documented Hoff (2011); Bazilian et al. (2011).

The approach is an important contribution in several ways. The consistent set of AHEAD indicators contributes to reducing current shortcomings in the measurement of social sustainability, regarding the arbitrariness of currently used indicators Littig and Griessler (2005). Further, linkages between the three pillars of sustainability can be assessed. As we were able to show with the example of water availability, changes in external factors, like climate change, can affect human well-being both directly and indirectly. Focussing on inter-linkages and associations between elements, the presented approach allows to assess how changes in one elements propagate through the system and lead to indirect effects and potential feedbacks.

While the approach gives some important insight, it also has several limitations. We are aware that the present framework is stylized and therefore provides a simplified model of real world processes. The results are valid at a generalized and global scale, but cannot reflect local or regional characteristics, which of course play an important role for individual and subjective human well-being. In order for the approach to provide applicable results to inform the potential policy-decision, localised case-study applications, taking into account local specificities and drawing on expert knowledge would be required.

In its present form it provides the first step of a formalization and provides a starting point for a subsequent detailed and rigorous analysis. Several limitations apply to the present identification of associations between elements. For the present implementation, these are solely based on scientific literature. On the one hand, this means that additional association may exist, which have not been documented. On the other hand, the underlying analyses which document existing association also use different methods in order to establish potential causalities. Such differences may lead to uncertainties and differences in the quality of the underlying assumptions. Such aspects would need additional consideration in a further elaboration of the approach. Additionally, association may vary according to regional specificities or cultural influences.

For the purpose of outlining and developing the approach, we denoted all relationships with the number 1, regardless of the intensity of the relationship. The present results therefore do not provide information on the strength or direction of the interaction. If more specific information on the relative intensity of connections is available, for example in regional or local applications of the approach, graduations or increments between 0 and 1 can be used within the influence matrix, thus further refining the specific positions of the elements within the system. Similarly, in a regional or local context additional (or fewer) elements may be needed to describe AHEAD, which are not documented in generally valid scientific assessments. A participatory assessment of local interconnections, drawing on expert knowledge, would be a useful realization of the approach for example.

It is important to note that the degree of activity/interconnectedness does not measure the absolute importance of the respective element of AHEAD. It only depicts the degree to which the element influences the other parts of the system, assuming that the system is bounded, and can thus give indications for where interventions may be most effective or where the possibility of unintended feedback may be high. The defined system boundaries affect the position of the elements within the influence matrix: the positions within the system may change if outside factors, additional elements or a different intensity of relationships are taken into account. Although we base our approach on a variety of approaches, it is possible that contrarian or alternative world views are not covered in the published literature and are consequently not covered by our approach.

The outline of elements of AHEAD as well as the qualitative assessment of associations and linkages give first important insights to interactions between determinants of human well-being, sustainable development and climate impacts. However, further research is needed in order to make the approach applicable, focussing on a case study setting. It is planned to implement and quantify the approach with available data to calculate detailed impact pathways and show in more detail how external impacts affect human well-being and livelihood conditions.

5 Conclusions

We have presented a flexible formalization of human well-being and livelihoods, conceptualizing the aspects identified in an influence matrix, based on generally valid, scientific findings. A fundamental novel aspect of the approach is its foundation in a range of established theories of human well-being and livelihoods, ensuring a comprehensive representation of requirements for human well-being with linkages to climatic impacts. The approach highlights the fact that integrated methodologies have to be developed to improve understanding of processes and interlinkages at the human-nature interface. With an approach as the one presented here, leverage points to maximize human welfare while working towards the much needed transition towards sustainability can be identified. As we were able to show, the system of AHEAD elements is highly interlinked and well-documented direct impacts on important sectors, such as food, water and energy will directly and indirectly affect important aspects of societal stability. With increasing levels of global warming, hot spots of climate impacts have to be expected. To prioritize adaptation along with efforts towards sustainable development, systematic knowledge on the constituents of human well-being in essential. The AHEAD framework contributes to the optimization of human well-being as a core part of sustainable development and to reconcile goals of sustainability with climate adaptation and mitigation.

3

Climate impacts on human livelihoods: where uncertainty matters in projections of water availability

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Abstract

Climate change will have adverse impacts on many different sectors of society, with manifold consequences for human livelihoods and well-being. However, a systematic method to quantify human well-being and livelihoods across sectors is so far unavailable, making it difficult to determine the extent of such impacts. Climate impact analyses are often limited to individual sectors (e.g. food or water) and employ sector-specific target-measures, while systematic linkages to general livelihood conditions remain unexplored. Further, recent multi-model assessments have shown that uncertainties in projections of climate impacts deriving from climate and impact models as well as greenhouse gas scenarios are substantial, posing an additional challenge in linking climate impacts with livelihood conditions. This article first presents a methodology to consistently measure Adequate Human livelihood conditions for wEll-being And Development (AHEAD). Based on a transdisciplinary sample of concepts addressing human well-being and livelihoods, the approach measures the adequacy of conditions of 16 elements. We implement the method at global scale, using results from the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) to show how changes in water availability affect the fulfilment of AHEAD at national resolution. In addition, AHEAD allows identifying and differentiating uncertainty of climate and impact model projections. We show how the approach can help to put the substantial inter-model spread into the context of country-specific livelihood conditions by differentiating where the uncertainty about water scarcity is relevant with regard to livelihood conditions - and where it is not. The results indicate that in 34 countries, livelihood conditions are compromised by water scarcity. However, more often, AHEAD fulfilment is limited through other elements. The analysis shows that for 65 out of 111 countries, the water-specific uncertainty ranges of the model output are outside relevant thresholds for AHEAD, and therefore do not contribute to the overall uncertainty about climate change impacts on livelihoods. In 46 of the countries in the analysis, water-specific uncertainty is relevant to AHEAD. The AHEAD method presented here, together with first results, forms an important step towards making scientific results more applicable for policy-decisions.

1 Introduction

Processes of global change are closely linked to human well-being and livelihood conditions. Global and regional impacts of climate change are expected to affect important societal sectors and have the potential to significantly reduce human welfare (Hare et al., 2011; Schneider et al., 2007; O'Brien et al., 2004). The linkages of various processes of global change to aspects of human well-being and livelihoods have been recognized in different contexts, including climate impacts (O'Brien et al., 2004), sustainable development (Dietz et al., 2009) and ecosystem services (MEA, 2005). While many approaches to define human well-being and livelihoods exist at various degrees of sophistication (O'Riordan, 2013; Alkire, 2002), an operable framework to assess and measure human well-being and livelihoods conditions in the context of climate change research does not exist so far. Yet, such a framework can provide an important means to assess the consequences of climate change for human welfare and societal systems, allowing to relate impacts of climate change to other development aspects and to compare impacts across sectors.

Uncertainty has proved to be a major impediment in climate-related policy decisions. Considerable uncertainty is associated with global models of climate and other biophysical processes, deriving from a range of factors (Schneider and Kuntz-Duriseti, 2002). Different types of uncertainty can be distinguished, some of which can be approached though further research or model improvement (epistemic uncertainty). Other aspects, such as uncertainty from scenarios, cannot be fully eliminated (aleatory uncertainty) (Dessai and Hulme, 2004). Uncertainty is an integral part of scientific analyses, however, in public perception it is often interpreted as ignorance or a lack of robustness (Sigel et al., 2010). To overcome barriers in the translation of scientific results into the policy process, uncertainty needs to be adequately framed (Smith and Stern, 2011). The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) (Warszawski et al., 2014) provides an important step towards explicitly and systematically addressing uncertainty deriving from climate impact models and emission scenarios and providing a consistent overview of the range of modelling results. While model improvements may reduce uncertainties to some extent, projections of future changes will always remain subject to aleatory uncertainties, as for example development pathways are not knowable. On the one hand, model- and scenario-related uncertainties can be made visible and quantified, as has been done with recent ISI-MIP results. On the other hand, methods to address the *relevance* of the uncertainty range for specific contexts can help in approaching the topic (Smith and Stern, 2011).

The central objectives of the present paper are two-fold, namely (I) to provide a method which addresses climate impacts in a wider context of human well-being and livelihood needs and (II) to show how this method can address the relevance of uncertainties within such assessments. While uncertainty itself is not reduced through the approach, its relevance for the system under consideration can be determined by viewing the uncertainty range in relation to a specific context. We first outline a novel methodology to measure *Adequate Human livelihood conditions for wEll-being And Development*, further referred to as AHEAD. Based on a transdisciplinary sample of concepts, the approach provides an integrated quantification of livelihood conditions, which allows assessing climate impacts in a comparable way. After an initial implementation of the approach on a global scale, we show how climate as well as population change may affect overall fulfilment of AHEAD. For a fist implementation of the approach, we focus on the example of water scarcity which has been identified as a major challenge of the future (Grey et al., 2013).

Recently, Schewe et al. (2014) analysed the range of ISI-MIP models to determine developments of water scarcity over the course of the next century. Results show significant uncertainty associated with the output of global water models, which is often even larger than the uncertainty deriving from climate models. We show how the AHEAD approach can provide a framework to view these uncertainties in a context.

Section 2 outlines the background of the AHEAD framework and presents its mathematical representation. We implement the approach in a first calculation, using freely available data at national resolution of global coverage. To underline the relevance of such an approach for climate impact research, we use results from the ISI-MIP project to outline the effects of changes in water availability on AHEAD. We assess in detail, how uncertainties associated with projections of potential future developments can be addressed within the framework. We analyse the results in Section 3 and critically discuss the method and results in Section 4. A brief conclusion completes our paper.

2 Methods and Materials

2.1 Identifying elements of AHEAD

The aim of the AHEAD approach is to quantify the Adequacy of Human livelihood conditions for wEll-being And Development, measured trough a set of elements. These elements include a range of tangible as well as intangible aspects, which represent an extended set of basic human needs (Littig and Griessler, 2005). Conceptually, elements of AHEAD are generally valid and globally applicable, allowing for a systematic and comparable assessment of livelihood conditions across space and time.

To derive a consistent set of elements to outline such conditions, AHEAD is based on a transdisciplinary set of approaches, identified trough a qualitative literature review (for a detailed outline of the conceptual basis of the AHEAD methodology see Lissner et al. (accepted)). On the basis of 11 theories, namely Maslow's Theory of Human Motivation

(Maslow, 1943), the Basic Human Needs Approach, (McHale and McHale, 1979; Doyal and Gough, 1984; Weigel, 1986), Human Scale Development (Max-Neef, 1992; Cruz et al., 2009) the Capability Approach (Sen, 1985; Anand et al., 2008; Gasper, 2007; Nussbaum, 2000), Human Security (Gasper, 2005; UNDP, 1994; King and Murray, 2001), Sustainable Livelihoods (Scoones, 1998; Chambers and Conway, 1991), Quality of Life (QoL) (Cummins, 1996; Costanza et al., 2007), Subjective Well-Being (SWB) (Diener et al. (1999), cited in Alkire (2002)), the Millennium Ecosystem Assessment (MEA, 2005), Dimensions of Poverty (Narayan et al., 2000) and the Measurement of Economic Performance and Social Progress (Stiglitz et al., 2009), we identify a set of 16 elements, which are relevant to measure AHEAD for climate impact research (see Figure 3.1). Detailed descriptions of AHEAD elements are available in the Supplementary Material, Table 1 (Lissner et al., 2014a, published on figshare).

In order to translate these identified elements into a quantified representation, we refer to the conceptual distinction between needs and satisfiers introduced by Max-Neef (1992) (see also Narayan et al., 2000; Sen, 1993). The *elements* of AHEAD (needs in Max-Neefs definition) constitute essential requirements to attain well-being and adequate livelihoods and are generally valid and globally applicable. However, the *satisfiers*, which can be used to access to these elements and meet needs may vary across space and time, for example according to cultural preferences or development status and various resources can contribute to meet needs. Further, following the underlying literature, no hierarchy can be assumed to exist between elements, with the exception of those elements directly relevant to physical survival (Max-Neef, 1992; Sen, 1993). For the purpose of measuring the fulfilment of AHEAD, we want to assess whether the availability of each element is *adequate* to meet human livelihood needs. Adequacy in this context refers to a situation, where elements are sufficiently available in quantity and quality to meet basic needs and permit a life in dignity (Wicks, 2012) as recognized for example in the Universal Declaration of Human Rights (UN, 1948). Adequate conditions therefore do not refer to a situation of luxury, but the sufficient availability of relevant resources. Similarly, inadequate conditions do not necessarily imply complete deprivation, but refer to a situation where livelihood needs are no longer met and development is compromised.

To facilitate the measurement of AHEAD, we group the 16 elements into three categories, (see Figure 3.1). Elements directly relevant to physical human survival are grouped into the domain of *Subsistence*, namely water, food and air. The remaining elements can be grouped according to their tangibility: aspects such as shelter and adequate sanitation provide essential *Infrastructure*. Further elements in this group include education, health care, as well as energy access, communication and mobility. Intangible aspects are relevant in their contribution to the *Societal Structure* and include social protection, security, participation, social cohesion as well as economic and political stability. In order to provide an estimate of comparable AHEAD at national resolution and global scale, we rely on data sets available at this level of detail and with as few missing values as possible.

The following paragraphs outline the method and discuss available data for a first implementation. We study in detail the relevance of changes in water availability for AHEAD over the course of the century, while the remaining elements are kept constant over time.

2.2 Integrating elements of AHEAD

Representing the concept of adequacy in mathematical terms can be difficult. The definition of exact thresholds of the sufficient availability of an element can be challenging, due to vagueness and uncertainties associated with such linguistic concepts. Fuzzy reasoning provides a means to express the degree of membership to linguistic concepts, thus translating qualitative elements into quantifiable units (for details see e.g. Kropp et al., 2006; Lissner et al., 2012; Zadeh, 1965) and allowing for the consideration of inherent vagueness. By calculating the degree of membership of each variable to a common linguistic category, namely the adequacy of conditions, the diverse range of elements become comparable with regard to their contribution to fulfilled AHEAD conditions.

The first step of the analysis is the fuzzification of the base variables with respect to a defined linguistic category. A function to calculate the degree of membership to the linguistic category is defined for each variable. In the case of our analysis, the degree of membership μ of each variable to the linguistic category "conditions are adequate" is determined. Fuzzified data sets take continuous values from 0 (adequacy is very low) and 1 (adequacy is very high). For the purpose of determining the fulfilment of AHEAD, fuzzy values near 0 reflect a basic level of resource availability, below which development would be compromised. Fuzzy values near 1 indicate a level of sufficiency, where basic needs are fully met and conditions are adequate.

Thresholds for membership (ι_1, ι_2) are defined to calculate continuous degrees of membership μ_{zi} of variable ι through Eq. 3.1 (linear increase), Eq. 3.2 (linear decrease), Eq. 3.3 (exponential increase) and Eq. 3.4 (exponential decrease). For Eq. 3.3 and 3.4, the value of ϵ determines the curvature of the function. For all Equations 3.1 through 3.4 $\iota_1 < \iota_2$ must be true. As the values for ι_1 and ι_2 critically determine the membership values for each element and thus the overall result, thresholds have to be context-specific and reflect the properties of the available data. Threshold values and membership functions for the analysis and are discussed in detail in the following Sec. 2.3 and are summarized in Table 3.1.

$$\mu_{zi}(\iota) = \begin{cases} 0, & \iota \leq \iota_1 \\ \frac{\iota-\iota_1}{\iota_2-\iota_1}, & \iota_1 < \iota < \iota_2 \\ 1, & \iota_2 \leq \iota \end{cases} \tag{3.1}$$

$$\mu_{zi}(\iota) = \begin{cases} 1, & \iota \leq \iota_1 \\ \frac{\iota_2-\iota}{\iota_2-\iota_1}, & \iota_1 < \iota < \iota_2 \\ 0, & \iota_2 \leq \iota \end{cases} \tag{3.2}$$

$$\mu_{zi}(\iota) = \begin{cases} 0, & \iota \leq \iota_1 \\ \frac{1}{1-\exp(-\epsilon)} \times \left(1 - \exp\left[-\epsilon\frac{\iota-\iota_1}{\iota_2-\iota_1}\right]\right), & \iota_1 < \iota < \iota_2 \\ 1, & \iota_2 \leq \iota \end{cases} \tag{3.3}$$

$$\mu_{zi}(\iota) = \begin{cases} 1, & \iota \leq \iota_1 \\ \frac{1}{1-\exp(-\epsilon)} \times \left(1 - \exp\left[-\epsilon\frac{\iota_2-\iota}{\iota_2-\iota_1}\right]\right), & \iota_1 < \iota < \iota_2 \\ 0, & \iota_2 \leq \iota \end{cases} \tag{3.4}$$

Subsequent to their fuzzification, variables are aggregated using context-specific aggregation rules in a defined order (Fig. 3.1).

The choice of aggregation rules should reflect the context of the analysis and be motivated by the properties of the indicators. Fuzzy decision rules thus allow incorporating the content-related properties of and relationships between variables. Operators for the aggregation are defined analogue to crisp set theory and additional fuzzy operators are available (Mayer et al., 1993). Unlike the strict application of boolean MIN or MAX operators, which result in a strict intersection or union of sets, fuzzy operators allow for compensation through a γ-value, which can take values between 0 and 1 (Equation 3.5 for fuzzy MIN; analogue quantification for fuzzy MAX) (Kropp et al., 2001). The introduction of γ results in the consideration of the arithmetic mean of all input values to some extent, thus diluting the strict application of the operator to the extent of γ, with values near to 1 resulting in a rather strict application of the operator and values near 0 introducing significant compensation. At γ=0 the arithmetic mean of the input values is calculated.

$$\mu(z_1 \wedge z_2 \wedge \ldots \wedge z_n) = \gamma \times \min(\mu_{z1}, \mu_{z2}, \ldots, \mu_{zn}) + (1-\gamma) \times \frac{1}{N}\sum_{i=1}^{N}\mu_{zi} \tag{3.5}$$

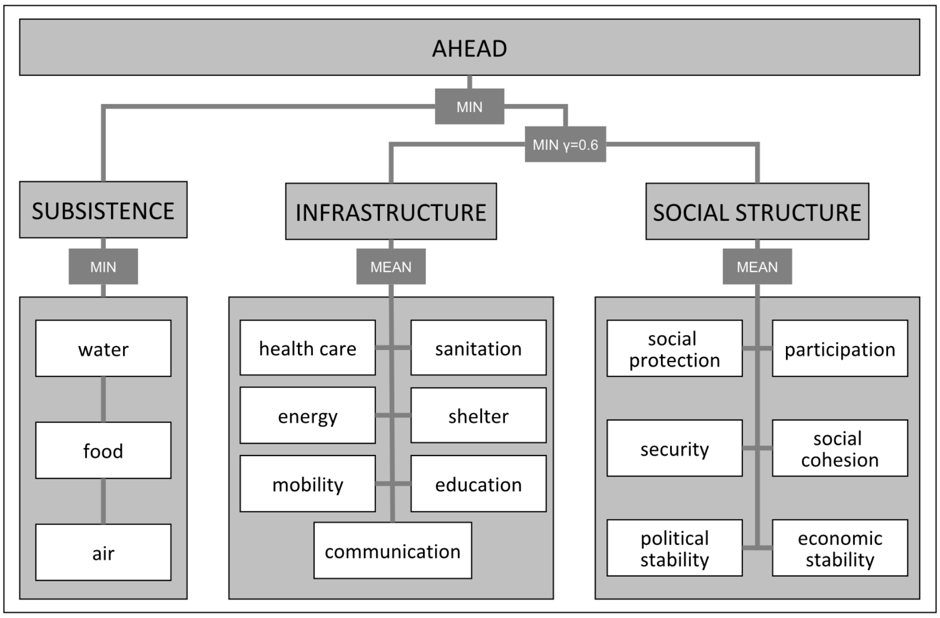

Figure 3.1: Overview of the fuzzy aggregation tree to calculate AHEAD. Detailed explanations of each variable as well as the aggregation procedures are given in Sections 2.2 and 2.3.

To assess the fulfilment of AHEAD, the characteristics of the contributing elements as well as their relationships determine the rules and order of aggregation, as outlined in Figure 3.1. Initially, the three dimensions of Subsistence, Infrastructure and Societal Structure are aggregated individually. An essential property of the elements of the Subsistence dimension is that they are non-substitutable: if one of the elements water, food or clean air is not available, it poses a direct threat to human health and well-being. Indicators within this dimension are therefore aggregated using a strict MIN operator with γ=1 (left column of Fig. 3.1). Elements relevant for the Societal Structure dimension, however, may to some extent be substitutable. Low availability of one resource may to some extent be compensated with the high availability of another, which is reflected in using the arithmetic mean (γ=0) (right column of Fig. 3.1). While those elements included in the Infrastructure dimension are not substitutable in a physical sense, high values in one of these domains imply high levels of technological advancement, which motivates the use of the arithmetic mean here (middle column of Figure 3.1). The final aggregation of the three dimensions to the full index of AHEAD reflects the fact that all three components are required to attain adequate conditions. We aggregate the dimensions Infrastructure and Societal Structure using a fuzzy MIN operator with $\gamma = 0.6$. This use of γ accounts for the fact that levels of adequacy in both dimensions are required for fulfilled livelihoods, but fully adequate conditions in one area may compensate other deficiencies to the extent of γ. While the order of magnitude and likely ranges of γ can be motivated by the context, the exact value is to some extent arbitrary within the in the global implementation of the approach. The subsequent aggregation of all dimensions to a measure of AHEAD is performed using a strict MIN operator ($\gamma = 1$), again reflecting the non-substitutability of the Subsistence domain.

2.3 Data and fuzzy membership functions to calculate the fulfilment of AHEAD

We implement the AHEAD index at global scale, relying on freely available data on national resolution (Table 1). As we rely on data sets that are available with global coverage, the consideration of possible satisfiers is limited in some cases, as only selected indicators are raised at this scale. Applied fuzzification methods for each variable are motivated by results from the literature as presented in Table 1. A more detailed summary of the translation of elements into a quantified representation in available in the Supplementary, Table 1 (Lissner et al., 2014a). Most elements can be represented with single datasets (Table 1). For the representation of some elements composite indicators have to be calculated, derived as follows:

- Water: sufficient water availability is essential both, directly, in terms of drinking water, as well as indirectly as an essential prerequisite for other elements, such as food and energy production. Drinking water availability is often not restricted by actual resource availability, but rather low quality or unimproved access are limiting factors (Rijsberman, 2006). Looking beyond physical water resources alone, 'water' is therefore represented using the two indicators 'access to improved water source', as well as 'available water resources', aggregated via a MIN operator. Adequate water resource availability refers to the cumulative water needs of all sectors.

- Air quality: both indoor and outdoor air quality determine health effects. The main determinant for indoor air quality is the use of solid fuels for heating and cooking, whereas negative health effects of outdoor air derive mainly from concentration of particulate matter (PM) (Klugman, 2011). The two indicators 'solid fuel use' and 'PM10 concentration' are aggregated using a MIN operator.

- Health care: the Human Development Index (HDI) includes the indicator 'life expectancy at birth' to represent the capability of leading a long and healthy life (Klugman et al., 2011). We combine the indicator with the average 'number of doctors per capita', using the arithmetic mean.

- Social protection: refers to a source of support available should one not be able to support oneself. In our analysis we identified three indicators, which can provide this support: 'institutional solidarity', 'traditional (community) solidarity' as well as 'access to micro credits' (de Crombrugghe et al., 2009). As either one of these can fulfill the need for support, we use a MAX operator for the aggregation.

- Economic stability: refers to conditions that enable the population to plan ahead and feel secure regarding the prospects for the future. We use the 'existence of labor legislation' and the degree of 'rigidity of employment contract' to represent 'economic stability' (de Crombrugghe et al., 2009). Indicators are aggregated with the arithmetic mean.

- Education: we use the HDI 2010 methodology (Klugman, 2011), which represents access to education with the two indicators 'mean years of schooling' as well as the 'expected mean years of schooling', aggregated with the arithmetic mean.

- Communication: we combine the indicators 'number of mobile phones' and 'number of internet users' as representatives of access to communication infrastructure, which have been recognised as essential tools of development (UN ICT Task Force, 2005), using a MAX operator.

Thresholds ι_1 ι_2, as well as the shape of the membership function (Eq.1-4) to fuzzify each input dataset, which are discussed in the following paragraphs, are motivated by literature (for an overview of all membership functions as well as the frequency distribution of the input data see Fig. A1a and A1b, Appendix). For the purpose of representing the adequacy of 'available water resources' for AHEAD, we use the Falkenmark Indicator, which defines a range of per capita water resource needs based on empirical estimates, including the domestic, agricultural and industrial sectors. We note that the application of such globally homogeneous thresholds represents a simplification which we deem appropriate for the purpose of the present, global study. Annual renewable water resources per capita (m^3 cap $^{-1}yr^{-1}$) below 500 m^3 cap $^{-1}yr^{-1}$ indicate absolute water scarcity (ι_1), while an availability of more than 1400 m^3 cap $^{-1}yr^{-1}$ indicates no water stress (water security) (ι_2) (Falkenmark, 1997; Brown and Matlock, 2011; Falkenmark and Rockström, 2004). Data sets for the variables 'access to improved water source' as an additional aspect of water availability, as well as 'access to improved sanitation' are grouped into three and four classes, representing the quality of access. For each country, the available data provides the percentage of households belonging to the respective class. To make use of this classification, we weigh each group according to the quality of access, as outlined in Howard and Bartram (2003). The classification and associated weights are as follows: access to water: (a) piped onto premises, weight 1, (b) other improved water source, weight 0.6 and (c) unimproved water source, weight 0.2; sanitation: (a) improved sanitation, weight 1, (b) shared facilities, weight 0.6, (c) unimproved sanitation, weight 0.2 and (d) open defecation, weight 0. The classes are then summed up, resulting in continuous values between 0 and 1, indicating the overall degree of adequacy of access.

It has been shown that a moderate increase in calorie intake has higher nutritional benefits at the lowest levels of calorie intake, approximated here by the use of a curved membership function (Equation 3.3) with $\epsilon = 3$ (Whitlock et al., 2009). Lower and upper thresholds refer to specifications by the FAO, who calculate minimum dietary requirement (MDER) for all countries, reflecting the demographic situation and propose a global average ideal nutrition level of 2800 calories $\text{cap}^{-1}\text{day}^{-1}$ (FAO, 2001). The effects of particulate matter on human health are especially strong at concentrations above 100ppm, while levels below 15ppm are acceptable (Desai et al., 2004); at lower concentrations health effects decrease (Pope III et al., 2002). The thresholds for the variables life expectancy at birth, as well as actual and expected mean years of schooling are set as used for the calculation of the HDI 2010 (Klugman et al., 2011). Adequate health coverage is likely to be achieved with a minimum health worker density of at least 0.0025 cap^{-1} and should be guaranteed at a density of 0.005 cap^{-1} (Chen et al., 2004).

Membership to the linguistic variable 'indoor air quality is adequate' is calculated using the indicator 'solid fuel use'. As some use of solid fuels can have lifestyle aspects, as for example in fireplaces (Lillemo and Halvorsen, 2013) we set the lower threshold to 5%, which represents fully adequate conditions. Membership decreases linearly up to a solid fuel use of 100%. We set the minimum electrification at 80% and calculate a linear increase of membership up to 100%, reflecting the fact that energy access is fundamental to many livelihood aspects, e.g. communication and most general household needs (Gaye, 2008) and restricted access also restricts many other livelihood needs. Both indicators for communication, the number of internet and mobile phone users, are fuzzified using continuous values between 0 and 1 cap^{-1}. For the fuzzification of mobility data we set ι_1 at 0.5 motor vehicles per cap^{-1}, as this reflects the lowest values of high HDI countries (World Bank, 2009). Similarly, ι_2 at 0.2 cap^{-1} reflects values in very low HDI countries.

Input data available to measure the Societal Structure are ranked continuously on a scale from 0 or 1 to 4. This ranking scale stems from the collection and preparation methodology of the data, where values of 0 mean that the respective element is not available at all, values near 1 represent low values and values of 4 indicate high availability or fulfilment of the respective element (de Crombrugghe et al., 2009). The linguistic representation of adequacy is thus already implemented in the initial classification and can directly be used in the fuzzy logic algorithm. Table 1 summarizes the relevant parameters for the fuzzification of elements and specifies the used datasets and sources (also see Supplementary, Table 1, for further details on the used indicators).

Data coverage differs slightly for the three dimensions of AHEAD and each dimension has missing values for some countries; the full measure was calculated for all cases with full data coverage across elements (111 countries). Shelter is the only aspect that cannot be represented adequately because of missing data and is therefore not included in the present analysis [1]. For the majority of indicators, no consistent scenarios are available. To address the question how potential climate change impacts may affect human livelihood conditions, we employ data from the Inter-Sectoral Impact Model Intercomparison Project ISI-MIP to address how changes in water availability affect AHEAD fulfilment.

2.4 Scenarios of water availability

For the analysis of water resource availability, we use global gridded runoff and discharge data, which has been calculated in the framework of the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP; Warszawski et al. (2014)). Simulations cover output by the impact models (IM) DBH (Tang et al., 2007), H08 (Hanasaki et al., 2008), Mac-PDM.09 (Gosling and Arnell, 2011), MATSIRO (Takata et al., 2003), MPI-HM (Stacke and Hagemann, 2012), PCR-GLOBWB (Wada et al., 2010), VIC (Liang et al., 1994), WaterGAP (Döll et al., 2003), and WBMplus (Wisser et al., 2010) hydrological models, the JULES (Best et al., 2011) land–surface model, and the LPJmL (Bondeau et al., 2007a) dynamic global vegetation model. The models were driven by bias-corrected (Hempel et al., 2013) climate data from five global climate models (GCM) that participated in the fifth phase of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. (2012)), based on four Representative Concentration Pathways (RCPs; (Moss et al., 2010)). As a first-order indicator of available renewable freshwater resources, we calculate annual mean runoff at each grid cell, and then redistribute it within each river basin according to the spatial distribution of discharge to account for cross–boundary flows between countries (Gerten et al., 2011). The result is summed up over every country and divided by the country's population to obtain water resources per capita per year. Country-level population data according to UNWPP estimates for the historical period, and according to the Shared Socio-economic Pathways SSP2 (O'Neill et al., 2012) projection for the future, is obtained from the SSP Database at https://secure.iiasa.ac.at/web-apps/ene/SspDb and linearly interpolated to obtain annual values. For further details about the model simulations, see also Schewe et al. (2014). We calculate average per capita water availability for a baseline of 1981-2010 (2000) and calculate projected changes for the scenario period 2071-2099 (2090). Years in brackets will be used throughout the paper as a reference to the 30-year average. We calculate water availability for each RCP and each IM-GCM

[1] Data on housing availability and quality is scarce. The available slum indicator used for measuring the Millennium Development Goals, for example, is an aggregate of five indicators: access to improved water, access to improved sanitation, sufficient-living area, durability of housing, security of tenure, of which only access to water and sanitation have acceptable coverage (143 countries, compared to 53 to 68 countries for the other indicators). Both of these indicators are resolved individually in the analysis. Source: http://www.unhabitat.org/stats/

Table 3.1: Indicators and data used to quantify elements of livelihoods. Column two and three specify the indicators and sources used for calculation of elements. ι_1 and ι_2 are the lower and upper thresholds to define the degree of membership. The last column provides the source and motivation for each of the thresholds. Where no source is indicated, underlying assumptions are discussed in the text. Note that the element 'shelter' is not included in the present calculation of AHEAD due to missing data (see footnote 1).

Elements	Indicator	Data Source	ι_1	ι_2	membership function	Source ι_1 & ι_2
water	internal renewable water resources	ISI-MIP (see Section 2.4)	1000 m^3 cap $^{-1}yr^{-1}$	1400 m^3 cap $^{-1}yr^{-1}$	linear increase	Appelgren (1998); Falkenmark (1997)
	access to improved water source	WHO (2009)	-	-	-	analogue to Howard and Bartram (2003)
food	calories $day^{-1}cap^{-1}$	FAOSTAT (2009)	country specific MDER[a]	2800 kcal	exponential increase (3)	FAO (2001); Whitlock et al. (2009)
air	PM10 concentrations	WHO (2009)	15 ppm	100 ppm	exponential decrease (1)	Desai et al. (2004); Pope III et al. (2002)
	solid fuel use	WHO (2009)	5%	100%	linear decrease	Lillemo and Halvorsen (2013) Desai et al. (2004)
sanitation	access to improved sanitation	WHO (2009)	-	-	-	analogue to Howard and Bartram (2003)
health care	life expectancy at birth	WHO (2009)	30	70	linear increase	Klugman et al. (2011)
	health care worker density	WHO (2009)	0.0025 cap^{-1}	0.005 cap^{-1}	linear increase	Chen et al. (2004)
energy	electrification rate	OECD/IEA (2009)	80%	100%	linear increase	see Sec. 2.3
education	mean years of schooling	UNDP (2009)	4	10	linear increase	Bhuwanee et al. (2009)
	expected mean years of schooling	UNDP (2009)	4	10	linear increase	Bhuwanee et al. (2009)
mobility	motor vehicles	World Bank (2009)	0.2 cap^{-1}	0.5 cap^{-1}	linear increase	see Sec. 2.3
communication	mobile cellular subscriptions	World Bank (2009)	0 cap^{-1}	1 cap^{-1}	linear increase	see Sec. 2.3
	internet users	World Bank (2009)	0 cap^{-1}	1 cap^{-1}	linear increase	see Sec. 2.3
social protection	institutional solidarity	IDP (2009)	2	4	linear increase	de Crombrugghe et al. (2009)
	traditional solidarity	IDP (2009)	2	4	linear increase	de Crombrugghe et al. (2009)
	micro lending	IDP (2009)	2	4	linear increase	de Crombrugghe et al. (2009)
political stability	political stability	IDP (2009)	2	4	linear increase	de Crombrugghe et al. (2009)
economic stability	labour legislation	IDP (2009)	2	4	linear increase	de Crombrugghe et al. (2009)
	employment contract rigorosity	IDP (2009)	2	4	linear decrease	de Crombrugghe et al. (2009)
security of person	domestic security	IDP (2009)	3	4	linear increase	de Crombrugghe et al. (2009)
social cohesion	social inclusion	IDP (2009)	2	4	linear increase	de Crombrugghe et al. (2009)
participation	population participation	IDP (2009)	2	4	linear increase	de Crombrugghe et al. (2009)

[a]Minimum dietary energy requirements (MDER): country-specific minimum requirement for minimum acceptable body-weight, taking into account demographic determinants (FAO, 2001).

combination individually and also calculate the average across models (ensemble mean). Per capita water availability is then translated into fuzzy values as discussed in the previous section. We include scenario data for water availability only, while other elements of AHEAD are kept constant over time. Changes in conditions are thus a function of changes in water availability over the course of the century.

Assessment of the relevance of uncertainty

Finally, we analyse AHEAD results with regard to the relevance of the uncertainty associated with the RCPs as well as the IMs and GCMs. As a result of the different levels of warming associated with the RCPa as well as differences between models, projections of future water availability differ, leading to a spread of results (inter-model spread).

We categorize our results according to the relevance that this inter-model and scenario spread has for the results of our analysis. Following the decision tree outlined in Figure 3.2, we differentiate several combinations, which determine whether the modelling and scenario induced uncertainty affect AHEAD results. As the inter-model and scenario spread leads to a range of possible values of water resource availability, there is a consequent range of possible fuzzy values of water availability for AHEAD conditions. "AHEAD spread" in the context of this analysis refers to the differences between the minimum and maximum possible values of aggregated AHEAD conditions as a result of the inter-model and scenario spread in projections of water availability in a given time period. In groups A, B and C.1/C.2 indicated in Fig. 3.2, the spread is not relevant with regard to the defined context-specific membership-functions and decision rules, and the country-specific result spread of aggregated AHEAD values is below 0.2. The result range is low, either because water is not limited (fuzzy water value of 1), regardless of the spread of the modelling output (A, C.1), because there is high agreement in the models and the result range is small (B) or because water is severely limited (fuzzy water value of 0) under all scenarios and models (C.2). For groups C.3 as well as all subgroups of D, the spread affects the results of fuzzy water values and overall AHEAD conditions and cannot be factored out. Here, we further differentiate results according to the magnitude of the spread. Group D.1 has a country-specific AHEAD result spread between 0.2 and below 0.5, whereas the result spread in classes D.2 are 0.5 or higher.

3 Results

3.1 Current and future fulfilment of AHEAD

The following paragraphs present the results of the analysis, based on the ensemble mean of the underlying scenarios of water availability. All country- and indicator-specific values

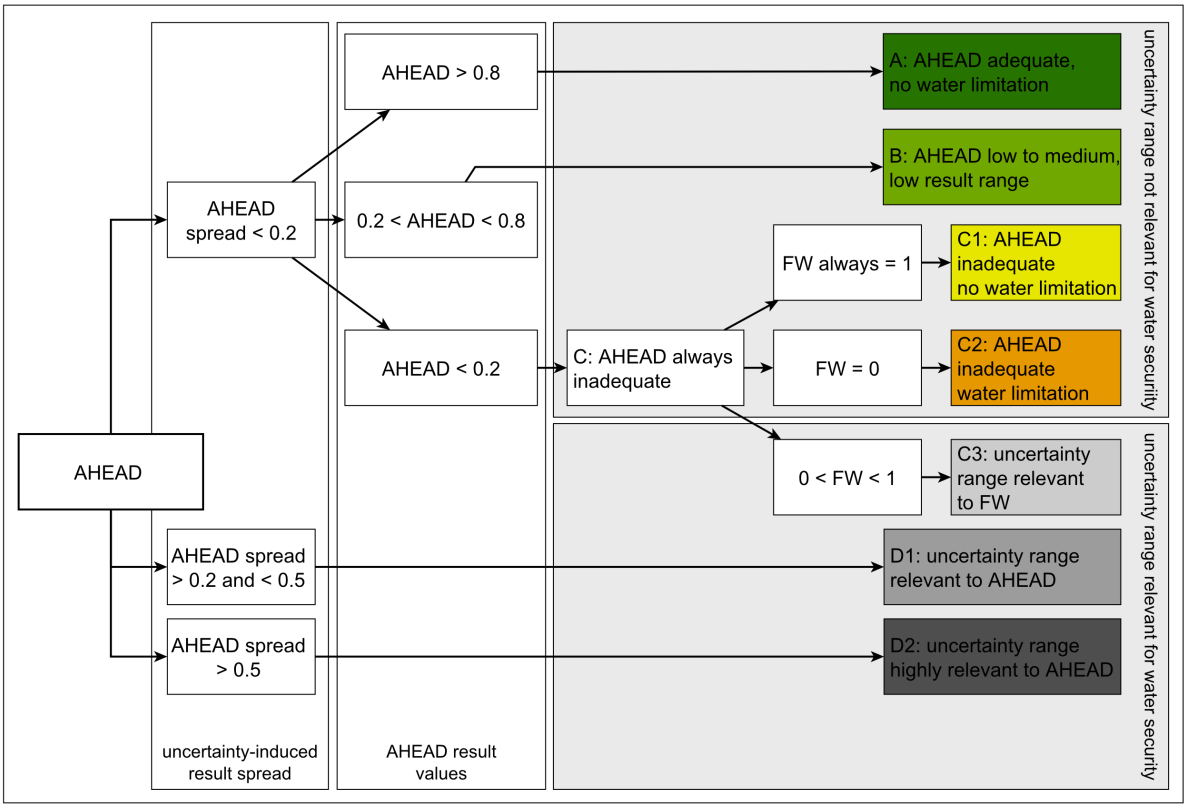

Figure 3.2: Decision tree to classify AHEAD results according to the result range of water availability data. Note that where the term 'range' is mentioned in the Figure, this refers to the range of result values for a single country, deriving from the range of values of water resource of availability from the different IM-GCM-RCP combinations. FW refers to fuzzified values of water availability. Classes A, B and C.1, C.2 comprise results, which show a low range of values, indicating that the uncertainty-induced result range lies outside relevant boundaries for adequate AHEAD conditions and water security. In classes C.3 and all D classes, uncertainty ranges are relevant with regard to AHEAD conditions and/or water security.

using the ensemble mean, as well as results of the individual IM-GCM-RCP combinations are available in the Supplementary Material (Lissner et al., 2014a). The initial fuzzification of all input values leads to comparable values between 0 and 1, describing the adequacy of each AHEAD element. The directed aggregation procedure then allows to quantify the adequacy of conditions of the three subindices Subsistence, Infrastructure and Societal Structure as well as the overall fulfilment of AHEAD. The fuzzified and aggregated values can be represented according to the degree of membership to the linguistic category of adequacy, ranging from very high (1 - 0.8), high (<0.8-0.6), intermediate (<0.6-0.4), low (<0.4-0.2) to very low (<0.2-0).

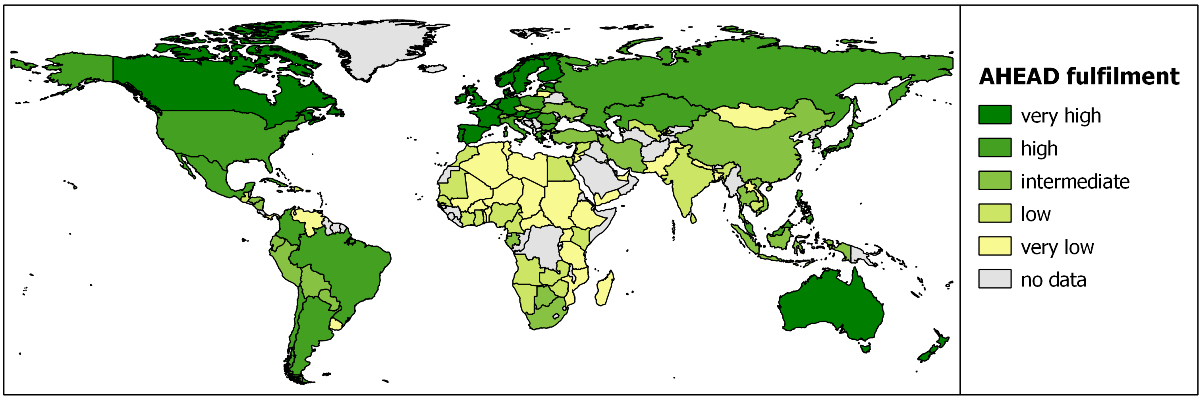

Figure 3.3: AHEAD fulfilment at global scale for present conditions (water data: ensemble mean across all participating ISI-MIP climate and water models for the baseline 2000.) Result values for current and future calculations for all GCMs and RCPs are published on figshare (Lissner et al., 2014a).

Figure 3.3 shows overall global livelihood conditions for baseline conditions (2000), using per capita water availability from the ensemble mean. Based on these values, global mean AHEAD fulfilment is intermediate (0.48). Only few changes in overall AHEAD fulfilment occur for the future scenario based on ensemble mean values, therefore only baseline values are presented in Figure 3.3. Calculations using the full range of ISI-MIP modelling results for baseline as well as the scenario period as input for water availability lead to a result spread of intermediate to low AHEAD fulfilment on global average (between 0.34 and 0.53). The general spatial distribution of AHEAD is similar across all scenarios and models. A total of 9 (22) countries consistently show very high (very low) AHEAD fulfilment in all model and scenario combinations, while in 80 countries the results vary as a result of different values of water availability.

When comparing the adequacy values for the three sub-indices in terms of the main limitations on the basis of the ensemble mean, in 47 countries the Societal Structure is most limited, while Subsistence and Infrastructure pose strong limitations in 37 and 27 countries, respectively. While this differs slightly across models and scenarios, as water limitations are higher or lower, nonetheless the general distribution is consistent and societal aspects limit AHEAD fulfilment in many regions. With the regard to the highest adequacy of conditions, in 51 countries values in the Subsistence domain are highest, while is true for 33 and 27 countries for the Societal Structure and Infrastructure domain (see Table A1 for a summary of the degree of fulfilment of all AHEAD elements and subindices; individual country values in the Supplementary).

Further zooming into the single elements of AHEAD, within the Subsistence subindex it is most often the inadequate air quality which limits the adequacy of conditions (baseline: 61, 2090: 59). On the basis of the ensemble mean, for the baseline in 34 countries water availability is the strongest limitation (36 for 2090 values), while calorie availability and water access limit the Subsistence subindex in 1 and 15 countries, respectively. Nonetheless, water limitations are also present in many regions, where other elements present the highest limitations to AHEAD. Of the 111 countries, 67 countries have fuzzy water values below 1, however in 32 of these, water availability is only slightly below the threshold and adequacy in very high. In 44 countries, no limitations are present (fuzzy water is 1) while in 21 countries, fuzzy water availability is below 0.6. The calculations for 2090 show slight reductions in the adequacy of water availability. In 43 countries water availability remains above thresholds of water security and in 27 countries the adequacy of water availability is very high. Countries with values of below 0.6 increase to a number of 30 for 2090. Within the Infrastructure domain, the elements mobility, energy availability and communication show the highest limitations, with minimum values in 52, 29 and 22 countries, respectively. In the Societal Structure, the main limitations show in the elements participation (59) and economic stability (22).

3.2 The relevance of uncertainties in projections of water availability for AHEAD

Uncertainties in climate impact analyses derive from various sources. In the present results, uncertainties deriving from the inter-model spread of both GCMs and IMs as well as from green-house gas scenarios are visible in the results, as they produce a range of potential future developments of water availability. Further sources of uncertainty, such as an incomplete understanding of underlying processes (see e.g Schneider and Kuntz-Duriseti, 2002, for a detailed overview) exist, however these are not in the focus of the present analysis. The AHEAD methodology allows to view the uncertainty-induced result range within a context, which allows determining whether this specific type of uncertainty is relevant with regard to a specific question, in this case the adequacy of water resources and AHEAD fulfilment. Where the remainder of the paper refers to uncertainty, this specifically refers to modelling and scenario induced uncertainties, which produce a visible result range (inter-model spread).

The basic idea of the approach is simple: if the uncertainty causes AHEAD results to cross the thresholds of adequacy, uncertainties are relevant to the fulfilment of AHEAD. If this is not the case, uncertainty is not relevant with regard to the specific context, here the adequacy of conditions. Figure 3.4 exemplifies in more detail, how the fuzzification and aggregation procedures allow assessing the relevance of uncertainty for AHEAD results, by showing three subsequent analysis steps in several example countries: plots on the left show the overall per capita water availability (m^3 cap $^{-1}yr^{-1}$). The middle and right plots present fuzzified values for water availability and AHEAD, respectively. In each plot, the individual IMs as well as the two timeslices are plotted individually, showing the result spread across GCMs and RCPs. Comparing the modelling results regarding water availability per capita (plots a-c), it is visible that Sweden in this example has the highest spread stemming from both, IM and GCMs, with modelled ranges of water availability of up to 13240 m^3.

When translating these values into a fuzzy representation of the adequacy of water availability (plots e-f), however, it becomes visible that this range is outside of values relevant to water security (fuzzy water availability is 1), as water supply in both countries is always adequate under all scenarios. The modelling and scenario related uncertainty present in the results is thus large, but is unlikely to affect human water security in the context of AHEAD. The two other examples Morocco and Ethiopia, have smaller results ranges of per capita water availability across models and scenarios. When translated into a fuzzified representation of water adequacy, however, it becomes clear that these ranges may be highly relevant to water security, as many of the potential future projections lie within a range of beginning or existing water scarcity. The third column (plots g-i) shows the resulting values of AHEAD for each country. In two of the examples, the result range of modelled water availability does not affect overall AHEAD conditions, either because the water availability is always above the relevant thresholds (Sweden), or because other factors determine the overall result (Ethiopia). In Morocco, water availability values are all within a critical range for water security and this remains visible within the overall results of AHEAD.

In this manner, the decision tree shown in Figure 3.2 allows to classify the results for each country according to the relevance of uncertainty for water security and overall AHEAD fulfilment. We use the value range across all models and scenarios for the classification, but differentiate between the time slices 2000 and 2090. The map in Figure 3.5 shows the resulting grouping of countries for baseline conditions, with grey colours representing groups with relevant uncertainty (C.3 and D). There are only few changes in this classification in the future scenario (see Supplementary Material for all country specific

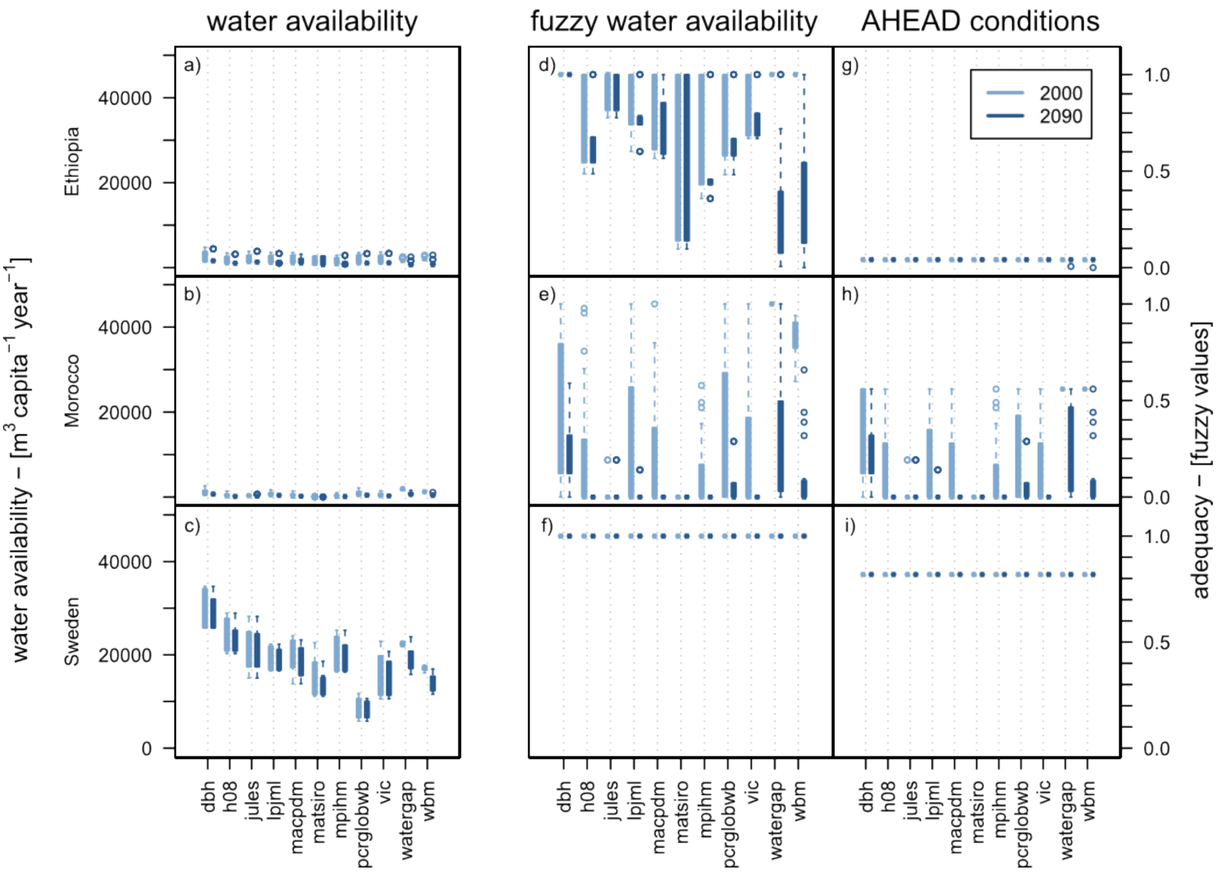

Figure 3.4: Examples of input data and fuzzified values/results for left: per capita water availability, middle: fuzzified water data, right: AHEAD results, for the examples Ethiopia, Morocco and Sweden. Right axis labels and units (adequacy [fuzzy values]) apply to middle and right panels. Results of the individual impact models are plotted from left to right within panels, showing the result range for all GCMs and RCPs for each timeslice.

values).

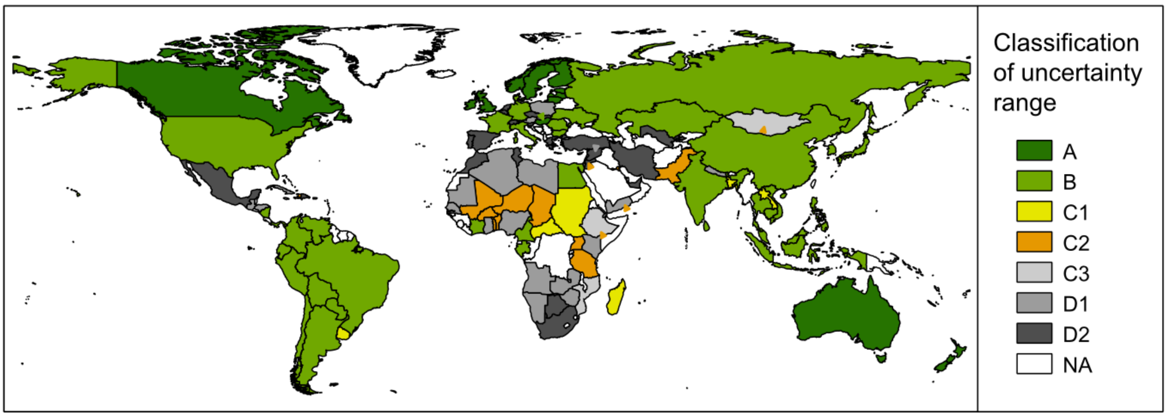

Figure 3.5: Classification of countries for baseline conditions following the decision tree outlined in Figure 3.2. Result values for current and future calculations for all GCMs and RCPs are published on figshare (Lissner et al., 2014a).

Of the 111 countries for which AHEAD could be calculated, at present in 65 countries the model spread is outside the thresholds for AHEAD fulfilment. This number increases to 70 countries in 2090, as water scarcity increases and water security is below minimum requirements in all RCP-IM-GCM combinations. The reduction of uncertainty is due to the high model agreement with regard to reduction in water availability to levels, where water scarcity has to be expected. Those countries, which move towards classes where uncertainty is not relevant to water security move to classes which show very low values of fuzzy water availability. In 46 countries (41 for 2090 values), uncertainty is relevant to highly relevant. Both for baseline and 2090 values, in 54 of the countries outside the uncertainty range, there is agreement between models and scenarios that water resources are adequate and fuzzy water values are high to very high. In 11 countries (16 in 2090), models agree on severe limitations to water availability (fuzzy water availability is 0).

4 Discussion

While information on sectoral climate change impacts is increasing, a generally applicable framework to relate climate impacts to livelihood conditions and human well-being has so far been unavailable. We present an approach to quantify *Adequate Human livelihood conditions for wEll-being And Development* and link these conditions to assessments of climate impacts, exemplified with changes in water availability. Based on a set of 16 elements to represent requirements for human well-being and livelihood conditions, the AHEAD approach provides a means to view climate impacts in a wider context, focussing on their relevance for human development.

The approach measures elements within the three dimensions of Subsistence, Infrastructure and Societal Structure. Conceptually, the identified elements of AHEAD constitute generally valid requirements for adequate livelihoods. Their fulfilment can be measured through indicators, representing the access to satisfiers, which can differ according to prevailing possibilities and preferences. In the present implementation, the focus in on a comparable measurement of AHEAD conditions at global scale and national resolution. The selection of indicators (satisfiers) is therefore limited to data which is available at this scale, but focusses on using comprehensive satisfiers to provide a holistic perspective, where possible. In the case of measuring social protection, for example, the three indicators 'traditional solidarity', 'institutional solidarity' and 'micro-credits/micro-lending' can each contribute to a very high degree of fulfilment, reflecting different cultural preferences and development status (Cook and Kabeer, 2009).

With regard to the representation of water availability within the AHEAD framework, our approach to combine water resource availability with the access to an improved water source provides an important way forward to account for the fact that water resources alone to not guarantee access to water. Especially in developing countries, water access infrastructure poses a more important limitation to water availability, rather than the available resource (Rijsberman, 2006). At the same time, water shortages to some extent can be mitigated by good water infrastructure. In many countries of the EU, such as Germany for example, per capita water availability is very close to a scarcity threshold, yet good water management so far has limited problems with water security. Both, changes in water resources as well as changes in population have an effect on the per capita resource availability within a country. By selecting average per capita requirements for a life in dignity as the assessment unit, the various pressures exerted on resources can be represented by the approach. In the case of water availability, it is often the increase in population which reduces the adequacy of per capita water availability, rather than reduction in water resources.

Methodologically, the use of fuzzy logic allows translating inherently fuzzy concepts and data from different sources and in different units into a consistent framework. The translation of elements from a qualitative description into a quantified representation is associated with vagueness. The use of linguistic categories as well as the representation of gradual truth values of membership to these categories provides a means to address this vagueness in a comparable way. The aggregation of data from different sources with different units is challenging (Parsons et al., 2011), as data needs to be transformed into a compatible format to enable aggregation. The definition of context-specific linguistic categories allows translating the range of input values into a consistent and comparable format, in the case of the present analysis a representation of the adequacy of conditions, allowing for direct comparison between countries. Other indicator-based approaches have been criticized for their normalization and aggregation methods, which do not retain important cause-and-effect relationships between elements (e.g. the well-known HDI: (Kovacevic, 2011).) Opposed to this, the AHEAD approach is not a simple aggregation of elements, but it allows to maintain properties of single variables in the final result.

The approach also allows assessing the effects of climate change impacts on AHEAD. As exemplified with the example of water availability, an assessment of the relevance of changes for a specific context, here the adequacy of AHEAD conditions, becomes possible. The approach can be extended in this regard, as it allows assessing a range of sectoral climate impacts. Projections of climate change and impacts are subject to uncertainty, deriving from several sources. Especially in climate impact assessments, uncertainties multiply along the assessment chain (Schneider and Kuntz-Duriseti, 2002). The present approach allows addressing parts of such uncertainties, by assessing their relevance with regard to a specific context. Of the sources of uncertainties, those deriving from the modelling set-up as well as from potential future scenarios are directly visible in modelling intercomparison efforts, such as the ISI-MIP project, as these make visible the range of plausible future developments. The methodology presented in this paper can help in putting these result ranges into a perspective, by analysing their relevance with regard to specific questions. In many cases uncertainty in future projections is high. However, as we were able to show with the example of water availability, often these uncertainty ranges do not overlap with critical thresholds for livelihood aspects, in this case, water security. As results presented in Figures 3.4 and 3.5 show, countries can be classified according to the relevance of uncertainty regarding water availability. In countries such as Sweden, modelling and scenario induced uncertainties are substantial, but all values are well above basic human requirements and therefore the uncertainties do not affect water security, as the fuzzification step from column 1 to column 2 in Figure 3.4 illustrates. In the examples of Ethiopia and Morocco, however, uncertainty remains relevant in this context.

The AHEAD approach also allows viewing changes in single components within a wider framework of livelihood conditions. Our results show that the majority of countries with low values of AHEAD are not water limited, but are otherwise restricted (Figure 3.5, class B and C.1) and other development priorities are more pressing. In many countries a large inter-model spread is apparent in projections of future water availability, as visible in the example Sweden. The translation into a fuzzy representation allows determining, whether this uncertainty is relevant with regard to a specific question. In Sweden, all projections are above the thresholds for water security. In countries such as Ethiopia and Morocco the inter-model is spread is lower, however the result range is highly relevant to livelihood conditions and water security and uncertainty remains visible in the AHEAD result. The approach can thus reveal important insights into development priorities. Modelling uncertainties have been blamed for inaction regarding climate change policies

(Lorenzoni et al., 2007). Such impasses can be resolved to some extent, if the visible uncertainty range is related to a specific context.

There are several limitations to the AHEAD approach and its present implementation. The use of global data at national resolution and the definition of globally applicable thresholds provides a comparable overview global AHEAD fulfilment, but is unable to include regional to local specificities. Country-specific management practices and preferences, for example, are thus not accounted for. An analysis at country-scale assumes, that national boundaries limit resource availability. However, especially in the food and water sectors, trade plays an important role for actual resource availability (Suweis et al., 2013; Chapagain et al., 2006). Additionally, the assessment of water requirements as an aggregate of all sectors does not take into account different sectoral requirements, with regard to quality and infrastructure for example. More detailed analyses at finer resolutions, as for example proposed by Lissner et al. (2014b), can provide important further information in this regard. Finally, the implementation at country-scale using annual mean water availability also assumes an even distribution of population and resources across space and time within country boundaries. Especially in large countries with uneven population distributions and diverse climatic conditions, such averages prove to be a limitation for the assessment of water availability.

The conceptual foundation of AHEAD is based on the ideas put forward in the literature of well-being and livelihoods. Following these ideas, the identified elements of AHEAD are non-culturally specific. However, the choice of indicators to represent their fulfilment (satisfiers) can vary, for example according development status or culturally-specific preferences. For the purpose of a global application, the availability of data sets of sufficient coverage is an important restriction. Some available data sets are limited in their ability to depict the potential range of satisfiers that could be used in order to meet the respective need. This is visible in the representation of mobility, for example. Mobility exists at different time-scales, different spatial scales and with different purposes. The focus of AHEAD is on short-term and local to regional mobility, which is relevant to social networks and inclusion, for example (Urry, 2003; Cass et al., 2005), but is also relevant to the accessibility of various services (Mokhtarian et al., 2001), such as health care for example (Molesworth, 2006). Existing indicators with sufficient coverage to present a global picture of mobility are scarce and the chosen indicator of motor vehicle density only represents a fraction of potential satisfiers for mobility needs. Similar restrictions apply to the other indicators used for the present calculation of AHEAD. Here, more targeted data-collection with a focus on regional specificities as well the different facets of satisfiers would be needed.

The current application of the index exemplifies how the relevance of uncertainty deriving from modelling approaches and scenarios can be assessed, using data on potential changes in water availability. For a holistic picture, consistent scenarios for all variables would have to be used, which is outside the scope of this assessment. It is also important to note that uncertainty ranges outside the thresholds relevant to AHEAD remain important for other water-related decisions, e.g. urban water flow management. While such changes may not directly affect water security, nonetheless other effects may negatively affect the adequacy of human livelihood conditions.

Knowledge on the biophysical impacts of climate change on global scale is becoming available at increasing levels of detail (Piontek et al., 2013), while assessments of impacts on societal systems and human livelihoods and well-being remain fragmented. The AHEAD approach proposes a framework which allows to systematically relate climate impacts to livelihoods at global to regional scales, providing a frame for the results of global modelling efforts. The adequate communication of research results is an essential requirement for the integration of scientific findings into policy decisions (Smith, 2011). Especially the role of uncertainty is often an impediment (Sigel et al., 2010). Embedding visible uncertainty of modelling output within a context allows showing where uncertainties are relevant with regard to specific questions and where they may be outside the range of relevance for the certain decisions. The results of course do not reduce the uncertainty of the modelling output, but they can help put existing uncertainties into a context. This may help in reducing the limiting and inhibiting effects that uncertainty currently has for climate change adaptation and mitigation policy decisions.

5 Conclusions

Uncertainty has been blamed for inaction in climate policy (Lorenzoni et al., 2007). This is also due to public misconceptions of the term uncertainty. The adequate and targeted communication of scientific results is essential in fields of high policy relevance, such as climate change research. To improve the communication and the transferability of results, adequate methodologies are urgently needed, which are rooted in scientific findings, but are able to bridge the gap between science and practice and are able to prepare results in an applicable and understandable way. The analysis and intercomparison of available impact models, as has been done in the ISI-MIP project, is an essential step towards the active consideration of uncertainties. By integrating these results into a wider context of human well-being and livelihood requirements, the AHEAD approach provides a novel way forward in the integrated and targeted communication of applicable scientific results.

4

A management model determining regional limits and sectoral constraints for water usage

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Abstract

Water is an essential input to the majority of human activities. Often, access to sufficient water resources is limited by quality and infrastructure aspects, rather than by resource availability alone, and each activity has different requirements regarding the nature of these aspects. This paper develops an integrated approach to assess the adequacy of water resources for the three major water users, the domestic, agricultural and industrial sectors. Additionally, we include environmental water requirements. We first outline the main determinants of water adequacy for each sector. Subsequently, we present an integrated approach using fuzzy logic, with allows assessing sector-specific as well as overall water adequacy. We implement the approach in two case study settings to exemplify the main features of the approach. Using results from two climate models and two forcing RCPs (Representative Concentration Pathways) as well as population projections, we further assess the impacts of climate change in combination with population growth on the adequacy of water resources. The results provide an important step forward in determining the most relevant factors, impeding adequate access to water, which remains an important challenge in many regions of the world. The methodology allows to directly identify those factors most decisive in determining the adequacy of water in each region, pointing towards the most efficient intervention points to improve conditions. Our findings underline the fact that in addition to water volumes, water quality is a limitation for all sectors and especially for the environmental sector, high levels of pollution are a threat to water adequacy.

1 Introduction

Water is a critical resource for human livelihoods and is needed for the majority of human activities. Pressure on water resources is increasing due to consumption as well as pollution, leading to situations of water scarcity in many regions of the world. Much knowledge exists regarding the single determinants of water scarcity, making clear that water shortages are often due to quality or access, rather than due to physical water shortages (Finlayson et al., 2012; WHO/UNICEF, 2000; WWAP, 2012; Sullivan, 2002). For example, assessments of human water requirements (e.g. Falkenmark, 1997; Falkenmark and Rockström, 2004) show, that the share of domestic water needs is comparably small. Nonetheless, domestic water scarcity prevails in many (developing) countries, mainly due to inadequate water quality and access (Rijsberman, 2006). Other important water users are the industrial and agricultural sectors, which each have distinct requirements regarding quantity, quality and access (Flörke et al., 2012; Falkenmark, 1997). Approaches such as the Water Poverty Index (Sullivan, 2002) and the Climate Vulnerability Index (Sullivan and Meigh, 2005) are important starting points to understand and integrate the multiple aspects of water scarcity and water poverty. Already today, human activities impact water availability and projected development pathways indicate further increases of these pressures deriving from population and economic growth (Bates et al., 2008). Additionally, climate change is expected to alter temperature and precipitation patters (Kirtman et al., 2013; Collins et al., 2013), potentially reducing available water resources and adding to existing situation of water scarcity.

The majority of societal activities require water and each sector has individual requirements. Planners and decision-makers require tools, which allow to view the multiple determinants in conjunction, to identify where potential limitations are most efficiently eliminated, also taking into account potential future changes. Existing approaches to assess water scarcity usually focus on single aspects of the topic, for example on human water requirements (e.g. Falkenmark (1997)), the relationship between water use and availability (e.g. Alcamo et al. (2003)), water consumption (e.g. (Hoekstra and Chapagain, 2006)), threats to water quality (e.g. Vörösmarty et al. (2010a)) or physical scarcity and drought (for comprehensive reviews see Eriyagama et al. (2009); Brown and Matlock (2011)). Focussing on peoples' daily realities, development oriented assessments of water access often address the aspect of water infrastructure (UN, 2012). It is also clear, that sufficient water needs to be retained for functioning ecosystems (Smakhtin et al., 2004), also with regard to the long-term adequacy of human livelihood conditions, however environmental aspects are seldom considered in assessments of human water scarcity.

This paper proposes a framework to assess the *adequacy* of water resources, integrating the various aspects which determine sectoral water security. Adequacy for the purpose of this analysis refers to a situation, in which the quantity, quality and access to water resources is sufficient to meet needs, but is not necessarily abundant or ideal. While knowledge on the single important aspects for the main sectoral water users is available, so far an integrated approach to account for sector-specific determinants of water adequacy is missing. The proposed method allows to distinguish between anthropogenic and physical causes of water scarcity, for example due to management or infrastructure problems (economic and social water scarcity; Brown and Matlock (2011)) or due to actual resource scarcity.

To retain important information regarding the most relevant determinants and to include context specific cause-and-effect relationships between variables, we propose the use of fuzzy logic. This method has been used in water resources research for example to assess issues of water quality (Gharibi et al., 2012) or wastewater reuse potentials (Almeida et al., 2013) and could be shown as a useful tool for integrating determinants of human-environmental systems (Kropp et al., 2001; Lissner et al., 2012). By identifying those factors most limiting to adequate water access, the results obtained through the proposed approach can directly inform decision-makers on how to most effectively improve access to water, extending the approaches put forward by Sullivan (2002) and Sullivan and Meigh (2005).

The objective is thus to integrate determinants of sectoral water adequacy into an overall measure of water adequacy, allowing to identify regional limitations as well as sectoral constraints to human water security. The analysis follows two subsequent steps. Initially, we identify criteria, which determine the adequacy of water resources for the main water using sectors and translate the identified determinants and their relationships into a methodological framework. We then apply the framework in two countries, Indonesia and South Africa, taking into account several scenarios of climate change, to outline where climate and population change may lead to additional water stress.

The analysis steps produce an integrated overview of the adequacy of water resources, while the applied methodology allows retaining important cause-and-effect chains which can point towards policy-relevant information. The following Sec. 2 gives an overview of the countries used as examples, outlines the analysis approach and introduces the methodological concept of the framework. We present the results in Sec. 3 and discuss them in Sec. 4, followed by some general conclusions.

2 Methods and materials

2.1 Case Study Regions

The two case study countries are presented in Fig. 4.1, showing the major cities as well as regional population densities. Both countries currently are at a intermediate human development stage. The 2012 Human Development Index (HDI) value for Indonesia is 0.629, with a rather strong increase from 0.422 since 1980. Like Indonesia, South Africa had a 2012 HDI value of 0.629, which is quite high above the average for Sub-Saharan Africa of 0.475 (UNDP, 2013). A higher development status usually results in increasing per capita water use, due to increasing water consumption across sectors. Both countries have positive growth rates in terms of population as well as economic growth, and this trend is expected to continue. Both, development and increasing water use will likely increase the total water withdrawal.

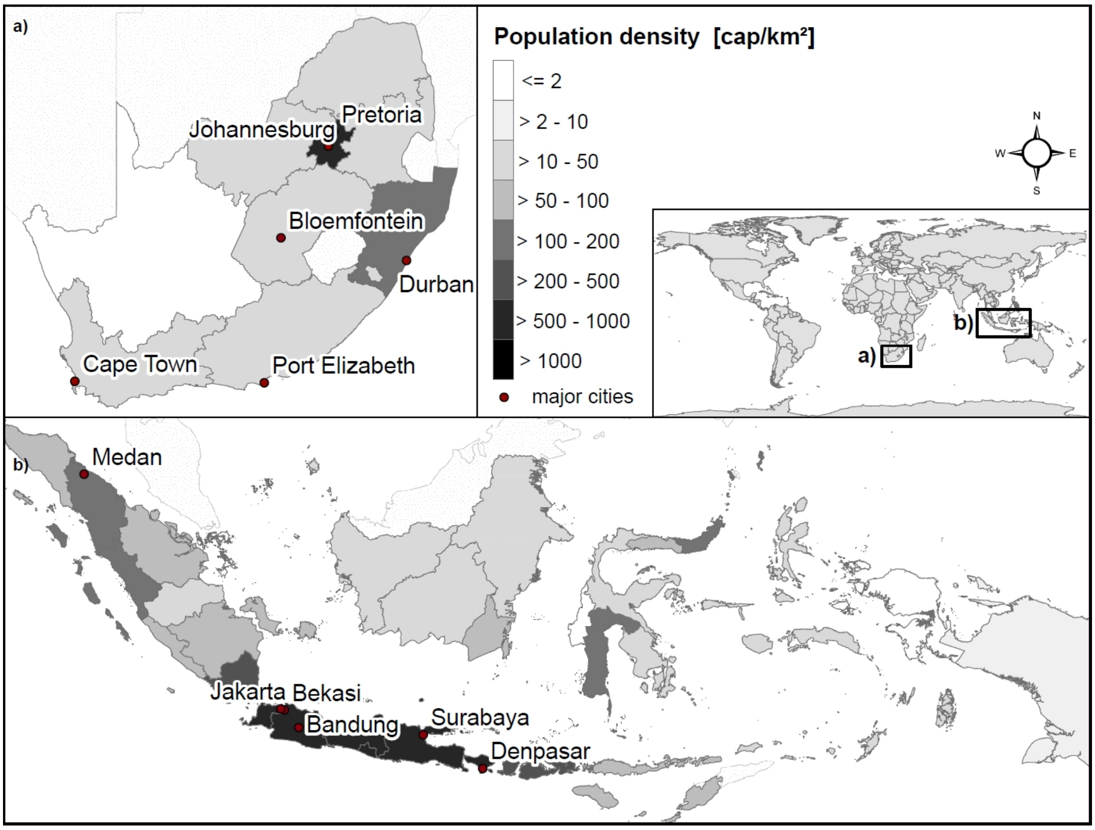

Figure 4.1: Regional population densities and major cities of the example countries a) South Africa and b) Indonesia and their location on the world map.

Indonesia is generally quite water abundant and currently withdraws 5.6 % of total renewable resources and per capita use is rather low at 531 $m^3/cap^{-1}/yr^{-1}$. The highest share of water goes towards agricultural use (82 %) and 6.5 % and 10 % are withdrawn for industrial and domestic use, respectively (FAO, 2011). Current per capita water use in South Africa is even lower at 284m^3 cap^{-1} yr^{-1}, however about 25 % of total renewable resources are currently withdrawn. This implies increasing pressure, as living standards rise and population increases. The distribution between sectors in South Africa is rather different with a relatively high fraction of domestic use at 31 %. 63 % go towards agricultural production and 6 % are used by industries (FAO, 2005).

2.2 Determinants and indicators to measure the sectoral adequacy of water

The most important sectors of human water use are the municipal (domestic), agricultural, energy production and industrial sectors (Flörke et al., 2012; WWAP, 2012; Falkenmark, 1997; Chenoweth, 2008). Sectoral attribution is sometimes ambiguous: the definitions of e.g. municipal and domestic water use overlap or are used interchangeably (Chenoweth, 2008; FAO, 2013; Flörke et al., 2012). Some estimations of water use and needs for agriculture include livestock production (FAO, 2013), while others account for the two sectors separately (Flörke et al., 2012). Further, water needs for energy and industrial production are often added up (Flörke et al., 2012) and are much more dependant on development status and country-specific conditions than other sectors (Chenoweth, 2008; Sullivan, 2002) (see Table 4.1 for details). For the purpose of the analysis, we distinguish the three sectors municipal, agricultural (including livestock) and industrial (including energy production), as this is the most common and applicable differentiation. An additional important aspect we take into account is the environment as a distinct water user, as functioning (aquatic) ecosystems and biodiversity are essential for healthy and sustainable living conditions and long-term water security (Smakhtin et al., 2004; Molle et al., 2010). For each of the sectors, specific determinants and water needs are differentiated in order to assess the overall water adequacy. The concept and main sectoral determinants are summarized in Fig. 4.2.

For an assessment of water adequacy, first sector-specific water resource needs have to be identified. Table 4.1 gives an overview of user/sector specific water needs estimated from the literature and converted to annual per capita water needs in m^3 (m^3 cap^{-1} yr^{-1}). Rather than the actual current water use, the table gives an overview of what has been identified as (minimum) sectoral needs. As the large differences suggest, estimations of water needs differ in their assumptions, and usually do not take into account external (imported) water. Chenoweth (2008) for example derives a rather low level of water needs, generalizing the current water use in the Netherlands. It is important to note, however, that imports of water through goods produced outside of the country are not taken into account here.

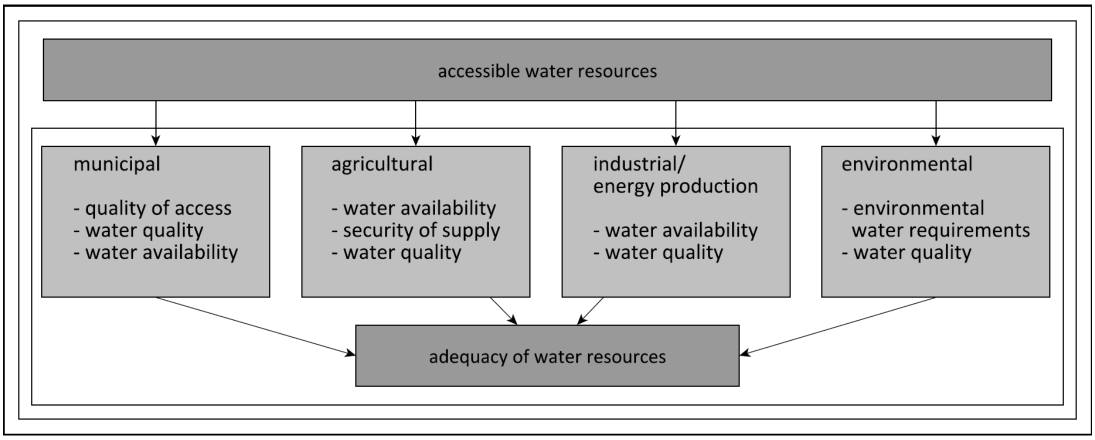

Figure 4.2: Conceptual overview of the determinants of sectoral water adequacy and the aggregation process.

Table 4.1: Overview of sectoral water needs according to different sources, all converted to $m^3/cap^{-1}/yr^{-1}$.

	Chenoweth (2008)	Falkenmark (1997)	Shuval (1992)	**Range**	**Threshold**
municipal	30.6	36	100	30.6–100	30–100
industrial	12.6	36–432	–	12.6–432	10–400
agricultural		504–1584	25	25–1584	500–1500
cumulative					**540–2000**

The most detailed analyses of generic, sectoral water requirements are the ones presented by Falkenmark (1997) and Falkenmark and Rockström (2004), which are amongst the most widely used indicators of water scarcity for global analysis. Here, water needs are assessed assuming all needs are met within country-boundaries. Further important accounts of municipal water needs include an analysis by Gleick (1998), who calculates a minimum domestic water requirement of $18\,m^3/cap^{-1}/yr^{-1}$, as well as a report by the Howard and Bartram (2003), where a range of 7.2 - $36\,m^3/cap^{-1}/yr^{-1}$ is identified. Accounts of generalizable environmental water requirements (EWR) have mainly been put forward by Smakhtin et al. (2004), who derive basin-specific EWR as a fraction of overall run-off. Values range between 20 and 50 % of total available resources. As opposed to assessing the sectoral water requirements, which is in the focus of the present analysis, existing models addressing water use focus on current and potential future withdrawal and consumption (Flörke et al., 2013; Lissner et al., 2014c). While these provide estimates of potential future developments, they do not assess whether available resources are sufficient in order to meet needs.

Additional to the availability of water resources in sufficient quantity, also quality and access determine water adequacy. Relatively little water is needed for the municipal sector. Here, access infrastructure as well as water quality are often a more important limitation to water adequacy (left part of Fig. 4.2) (Rijsberman, 2006; Sullivan, 2002). Rather than looking at resource availability, access to an improved water source is central to the Millennium Development Goals (MDG), for example (UN, 2012). Water quality aspects are also of utmost importance for the municipal sector, as low quality of drinking water has direct consequences for human health (Howard and Bartram, 2003) and may render water non-potable without prior purification (Finlayson et al., 2012). In their assessment of the main threats to global water security Vörösmarty et al. (2010b) identify several relevant pollutants with direct negative health effects, including nitrogen, phosphorus, pesticides, mercury as well as organic matter and high sediment loads[1].

Water needs of the industrial and energy sectors are diverse (middle left of Fig. 4.2). Water is eventually needed at some stage of the production process, but quantity, quality and other requirements depend strongly on the specific process (Graedel and van der Voet, 2010; WWAP, 2012). A common denominator is the need for cooling water, which is generally needed in production processes, for which some general requirements can be identified (Morrison et al., 2009). Low water quality can increase costs, as water has to be prepared for use. Especially high quantities of suspended sediments can damage turbines (Graedel and van der Voet, 2010; Vörösmarty et al., 2010b; Morrison et al., 2009). Higher water temperature may also reduce the availability and usability of water for cooling purposes (Graedel and van der Voet, 2010; Vörösmarty et al., 2010b; van Vliet et al., 2012). Though low water quality does affect industrial production, it is more often a cause of water pollution itself.

About 70 % of withdrawn water goes towards agricultural production (WWAP, 2012) and overall resource availability is the most critical factor for the adequacy of agricultural water (middle right of Fig. 4.2). Seasonal variability and short-term shortages may be buffered through water storage (dams) as well as through the availability of irrigation infrastructure. While dams may have negative ecological effects for ecosystems, they can increase human water security, both through water storage for situations of shortages, as well as through potential buffering during flooding events (Vörösmarty et al., 2010b; Finlayson et al., 2012). Agricultural production in general may be less dependant on water quality, rather the sector contributes strongly to water pollution. Quality factors which may reduce yields are mainly related to potential salinisation (Vörösmarty et al., 2010b).

Environmental water requirements (EWR) refer to the fraction of water, which should remain within aquatic ecosystems to ensure adequate long-term ecosystem health and sustainability (Fig 4.2, right). Basin-specific EWR depend on prevailing regional climate conditions and vegetation (Smakhtin et al., 2004). Water pollution is an additional critical determinant of ecosystem health and multiple sources of human activities affect water

[1]For details on the background of all indicators of water quality used throughout this paper see Vörösmarty et al. (2010b)

quality and pollution levels, threatening biodiversity (Vörösmarty et al., 2010b).

Summarizing the determinants of sectoral water adequacy, Table 4.2 gives an overview of the proposed indicators for the subsequent analysis. Column 2 specifies the indicator name, as used in the remainder of the paper. Columns 3 and 4 summarize the variables and data sources, which are used to quantify each indicator. The data are also discussed in more detail in the following Section 2.3.

2.3 Fuzzy logic approach to measuring water adequacy

A fuzzy logic approach is developed to translate the sector-specific determinants into an integrated measure of water adequacy. Fuzzy logic allows converting qualitative or inherently fuzzy concepts into mathematical representations, by defining linguistic categories and translating the input values into degrees of membership (μ_{zi}). For the process of fuzzification, upper and lower thresholds ι_1 and ι_2 are defined which determine the degree of membership of values to the respective linguistic categories. Further, the shape of the function (e.g. linear, exponential) determines the degree of membership of each element. The fuzzified variables take continuous values between 0 and 1, representing the degree of membership to the respective concept (see e.g. Lissner et al., 2012; Kropp et al., 2001, for details). For the purpose of the present analysis, we want to calculate the *adequacy* of the determinants of water availability, quality and access to derive an integrated measure of water adequacy, where values near 1 indicate highly adequate conditions and values near 0 indicate inadequacy of the respective component. Equation (4.1) describes the process of fuzzification for linear membership functions, as used for the purpose of the present analysis.

$$\mu_{zi}(\iota) = \begin{cases} 0, & \iota \leq \iota_1 \\ \frac{\iota - \iota_1}{\iota_2 - \iota_1}, & \iota_1 < \iota < \iota_2 \\ 1, & \iota_2 \leq \iota \end{cases} \tag{4.1}$$

Following the process of fuzzification, the variables can then be aggregated using context-specific decision rules, which allow to account for relationships between variables. Decision rules should be chosen according to the specific properties of the variables and the analysis. Operators include strict minimum (AND) and maximum (OR) operators as well as averages such as as harmonic, geometric and arithmetic mean (Mayer et al., 1993). Fuzzy logic further offers the possibility to include the compensating element γ, which allows using fuzzyAND (Equation 4.2) and fuzzyOR operators by taking into account the arithmetic mean to the extent of γ, with γ-values near 1 resulting in a strict application of the operator and values near 0 actually calculating the arithmetic mean

(Kropp et al., 2001). Figure 4.3 outlines the aggregation process, showing current values for South Africa. The aggregation for Indonesia follows the same procedure. For each sector, two main aspects are considered: these include the fuzzified determinants of access and quality (middle column, Fig. 4.3) as well as the fuzzified adequacy of water availability (right column). We first calculate individual sector adequacy and subsequently aggregate all values to an integrated measure of water adequacy. Each step of fuzzification and aggregation follows a context-specific reasoning-process.

$$\mu(z_1 \wedge z_2 \wedge \ldots \wedge z_n) = \gamma \times \min(\mu_{z1}, \mu_{z2}, \ldots, \mu_{zn}) + (1-\gamma) \times \frac{1}{N}\sum_{i=1}^{N} \mu_{zi} \tag{4.2}$$

Fuzzy reasoning-process and data preparation

In order to represent the various factors which influence the adequacy of water, we focus sources which provide comparable and consistent estimates for both countries. The data and fuzzification process to represent the sectoral determinants are outlined in the following paragraphs and summarized in Table 4.2.

Table 4.2: Overview of data sources (variables) used to represent the indicators of water adequacy.

Sector	Indicator	Variable	Source
Municipal	municipal water access (m_access)	M1: Source of drinking water	ICF (2013)
	municipal water quality (m_quality)	M2a: Phosphorus loading	Vörösmarty et al. (2010b)
		M2b: Nitrogen loading	
		M2c: Sediment loading	
		M2d: Organic loading	
		M2e: Mercury deposition	
		M2f: Pesticide loading	
Agricultural	agricultural water quality (a_quality)	A1: Soil salinisation	Vörösmarty et al. (2010b)
	security of supply (a_sec_supply)	A2a: Dam density	
		A2b: Area equipped for irrigation	AQUAstat (FAO, 2013)
Industrial	industrial water quality (i_quality)	I1: Sediment loading	Vörösmarty et al. (2010b)
		I2: Thermal alteration	
Environmental	environmental water quality and biodiversity threat (biod_threat)	E1: Biodiversity threat	Vörösmarty et al. (2010b)
Water availability	available water resources (all_water)	W1: Total runoff (surface and subsurface)	LPJmL (Bondeau et al. (2007b); Warszawski et al. (2014))

Vörösmarty et al. (2010a) provide a comprehensive global database of water quality indicators for the year 2000, which we use to represent the individual indicators of water quality for each sector. The available data provides estimates of water quality at global scale for various indicators. Where data from this source is used, it was prepared as follows: data are originally provided as values between 0 and 1, where values near 0 indicate low threat intensity and values near 1 indicate severe threats to water security. We calculated the mean threat intensity for the administrative regions of the two case study countries and invert these values, so that values near 1 indicate adequate water quality (low pollution threat) and values near 0 indicate low water quality (high pollution threat). Therefore, no further fuzzification is required for these values.

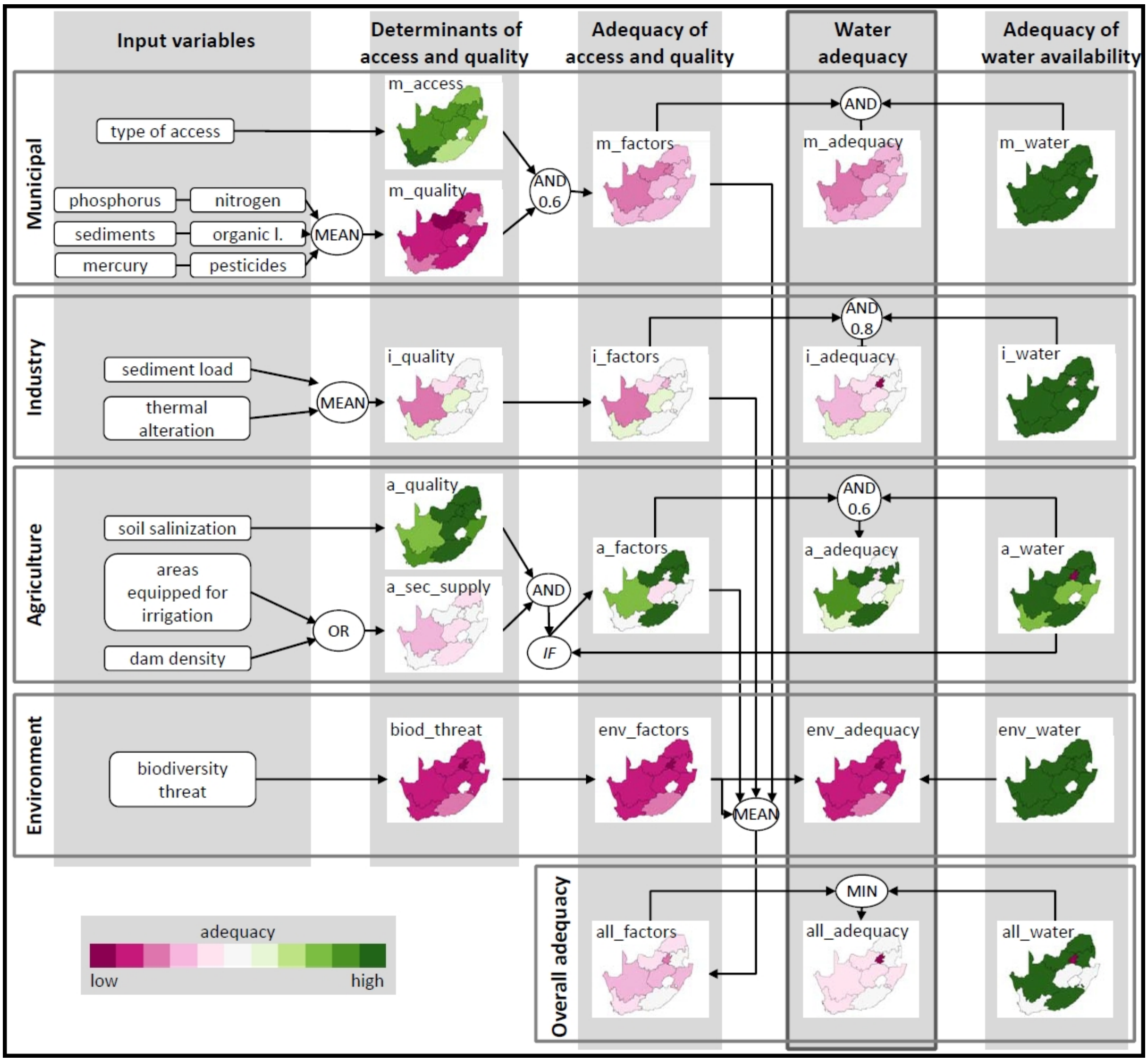

Figure 4.3: Fuzzy aggregation tree to calculate the adequacy of available water resources. Maps show values for South Africa using water availability data from the HadGEM2-ES model under current conditions (HADbase).

Municipal water adequacy

In the case of municipal water adequacy, infrastructure to access water resources plays an important role. To measure municipal water access, improved and unimproved water sources are differentiated (Howard and Bartram, 2003; ICF, 2013). The MEASURE Demographic and Health surveys (ICF, 2013) provide access to detailed indicators, aggregated to administrative regions (M1, Table 4.2). To represent the adequacy of access to drinking water (m_access), we weight the different types of access according to their adequacy (weights adapted from Howard and Bartram (2003), Table 6). Water piped onto the premises has a weight of 1, access through a well has weight of 0.5, while all other types of access have a weight of 0.2. The sum of the weighted access types returns values between 0 and 1, where values near 1 indicate highly adequate m_access (i.e. a very high proportion of population with water piped onto premises), whereas values near 0 indicate inadequate m_access. Also water quality plays a prominent role. Contaminated drinking water either renders the water non-usable or threatens human health. Various aspects determine municipal drinking water quality (m_quality) (see Sec. 2.2). The most important contaminants which affect municipal water quality as identified by Vörösmarty et al. (2010a) are phosphorus loading (M2a), nitrogen loading (M2b), sediment loading (M2c), organic loading (M2d), mercury deposition (M2e) as well as pesticide loading (M2f).

High quality water infrastructure (m_access) plays an important role in mitigating potential negative effects of low water quality in the municipal sector (m_quality). For the aggregation of the municipal determinants of access and quality (m_factors), this translates into the fuzzy reasoning process as a fuzzyAND operator, where both aspects have to be sufficiently available for adequacy to be high. However, as highly adequate access infrastructure can reduce contaminants, a γ-value of 0.6 is introduced, allowing to compensate to some extent (Fig. 4.3, column 3). While comparatively little water is needed to fulfil municipal water needs (m_water), nonetheless water availability is obviously essential and a strict fuzzyAND is applied to aggregate the overall measure of municipal water adequacy (m_adequacy) to account for this fact (Fig. 4.3, column 4).

Industrial water adequacy

The common denominator to assess industrial water adequacy is the availability of cooling water of sufficient quality, which can be represented by the sediment load (I1) as well as water temperature (thermal alteration, I2) (Vörösmarty et al., 2010b). Both, the quality (i_quality) as well as sufficient water availability (i_water) determine the adequacy of industrial water resources (i_adequacy), however, low water quality does not completely inhibit cooling water extraction. We therefore use of fuzzyAND with a γ-value of 0.8 aggregate the indicators for the overall measure of industrial water adequacy (i_adequacy).

Agricultural water adequacy

For the agricultural sector as the highest water user, sufficient water availability (a_water) is most important (W1, see also Table 4.1). Infrastructure to buffer potential shortages can reduce the risk of inadequate water supply. Both the availability of dams as well as irrigation infrastructure can provide such infrastructure. As either of these two indicators may increase water security, these are aggregated using a fuzzyOR. Dam density (A2a) is included in the river threat database (Vörösmarty et al., 2010a) and prepared as described. Similarly, data on areas equipped for irrigation (A2b) is provided in percentage values and is averaged over the administrative regions. Finally, water quality for the agricultural sector (a_quality) is represented by the potential soil salinisation (A1) (Vörösmarty et al., 2010a). Infrastructure to ensure the security of supply of water for agriculture (a_sec_supply) is especially important in regions where available water resources are close to or below thresholds of water needs. To account for this, we introduce an if-clause into the analysis: only if water availability is below the threshold of adequacy, supply infrastructure becomes relevant for the analysis. Where water availability is limited, the security of supply indicator plays an important role. As slight shortages in water availability can be compensated in this way, a γ-value of 0.6 is introduced to combine adequacy of access and quality (a_factors) with water availability (a_water) for the agricultural sector.

Environmental water adequacy

Environmental water requirements (EWR) are prioritized in our analysis in the following way: we assume that sufficient water is retained for ecosystems by deducting EWR from the overall water resources, before assessing water availability for other sectors. Smakhtin et al. (2004) calculate basin-specific EWR as a percentage of overall run-off, ranging between 20 and 50 % of total available resources. We average these values over the administrative regions of the case study countries and subtract the respective fraction from the overall water available in the respective region. The remaining water is then available for human use in three sectors, while keeping water availability within sustainable environmental boundaries. Environmental water quality is represented by an integrated indicator of biodiversity threat (biod_threat, B1), representing relevant pollution and disturbance factors (Vörösmarty et al., 2010b).

Currently, no projections of the potential future development of the introduced variables are available. Therefore, values for the assessment of current as well as short-term future water adequacy are kept constant for aspects of access and quality. Projected changes derive from the variables water availability as well as population.

Scenarios of water availability and population

Water availability for the purpose of the analysis describes the total internal renewable water resource, as required for the assessment of water scarcity according to Falkenmark (1997) and Falkenmark and Rockström (2004). To measure water availability and calculate future scenarios of climate change impacts, we use output from the Lund-Potsdam-Jena managed Land (LPJmL) model, a dynamic global vegetation and water balance model (Bondeau et al., 2007b). Specifically, we use the mean total surface and subsurface runoff per grid cell. We make use of publicly available results generated within the framework of the Inter-Sectoral Impact Model Intercomparison Project process of the Intermodel fasttrack process (ISI-MIP; Warszawski et al. (2014)).

Calculations are based on two Representative Concentration Pathways (RCP) as forcings for the two employed Global Climate Models (GCM) HadGEM2-ES and GFDL-ESM2M (van Vuuren et al., 2011). We calculate mean annual water availability for a baseline (1981-2010) and a short term (2011-2040) scenario, based on the two GCMs, using RCP2.6 and RCP8.5. The GCM-RCP combinations are further referred to as: HADbase, HAD2.6, HAD8.5, GDFLbase, GDFL2.6 and GDFL8.5. Similar to the preparation of water quality data, we calculated values for the administrative regions, summing up the cell values to derive yearly values of water availability per administrative unit. To assess per capita availability, we rely on regionalised population projections from the National Statistical Offices for the case study regions and divide the total available water resource by the population (Indonesia: BAPPENAS (2005), South Africa: van Aardt (2007)[2]). In both countries, population is expected to increase in the coming decades. Projections of water resources indicate marginal change in overall water resource availability for both countries, with larger differences between the two GCM than between RCPs and the timeslices. All input data for the administrative regions is published in the Supplementary Material at figshare (Lissner et al., 2014d).

In order to assess the adequacy of available water resources using fuzzy values, (m_water, i_water, a_water and all_water), we use the rounded lower and upper ranges as identified in Table 4.1 (column "Thresholds") for the process of fuzzification. Here, the lower identified threshold refers to the minimum water need identified in the literature and the upper threshold denotes a situation of adequacy. To derive individual values of adequacy for each sector, initially we assume that the total water resource would be available to

[2]Available subnational projections for South Africa exist up to the year 2021; we applied the national available growth rates to the projected data for 2021 to derive values for 2025

meet the needs of the single sectors. To then assess the overall adequacy of water availability across all sectors, the needs of all sectors are summed to assess the cumulative adequacy of overall water resources (all_water).

To finally derive an integrated indicator of overall water adequacy (all_adequacy), sectoral quality and access aspects are combined with the overall water needs across sectors. For the purpose of exemplifying the approach, we use a MEAN operator to aggregate all sectoral determinants of access and quality (all_factors), but combine this indicators with the overall water availability (all_water) using a strict MIN operator, reflecting the fact that sufficient resource availability is a prerequisite.

3 Results

The overall adequacy of water is a function of all factors which affect the quantity, quality and access to water by relevant sectors. Besides outlining the aggregation procedure, Fig. 4.3 also presents results in the form of maps, representing the fuzzified and aggregated values for South Africa for each analysis step for current conditions of water availability (GDFLbase). The analysis is conducted calculating the degree of membership to the linguistic category 'conditions are adequate', which translates into results of water adequacy ranging from very high (0.8-1), high (0.6-0.8), intermediate (0.4-0.6), low (0.2-0.4) to very low (0-0.2). As generally visible, access factors critically determine the resulting values of water adequacy: while the adequacy of available water resources is (very) high in terms of quantity for most sectors, access and quality have a strong influence on the results.

Water quality plays an especially important role for the adequacy of municipal water resources in South Africa. Though the adequacy of access (m_access) is high to very high, municipal water quality (m_quality) is (very) low and leads to inadequate municipal adequacy of access and quality (m_factors). For the industrial sector, available resources suffice to meet needs, but alterations of quality reduce its adequacy in all regions. Due to the high agricultural water needs (a_water), limitations are faced in some regions of South Africa. Both, the areas equipped for irrigation as well as the dam density are rather low, thus the security of supply is often insufficient to buffer potential shortages. Nonetheless, agricultural adequacy (a_adequacy) is intermediate to high all over South Africa. The integrated indicator depicting regional biodiversity threat shows that water quality pressure on the environment is high, negatively affecting the environmental water adequacy (env_adequacy). The mean adequacy of determinants of access and quality as a combination of all sectoral determinants (all_factors) is low to intermediate. The sum of sectoral water requirements (all_water) shows limitations in resource availability, especially in densely populated areas, hinting at potential competition between sectors. The overall result depicting water adequacy (all_adequacy) is an aggregate of all input factors and cumulative water requirements of all sectors, mainly reflecting the limitations in access and quality factors across regions.

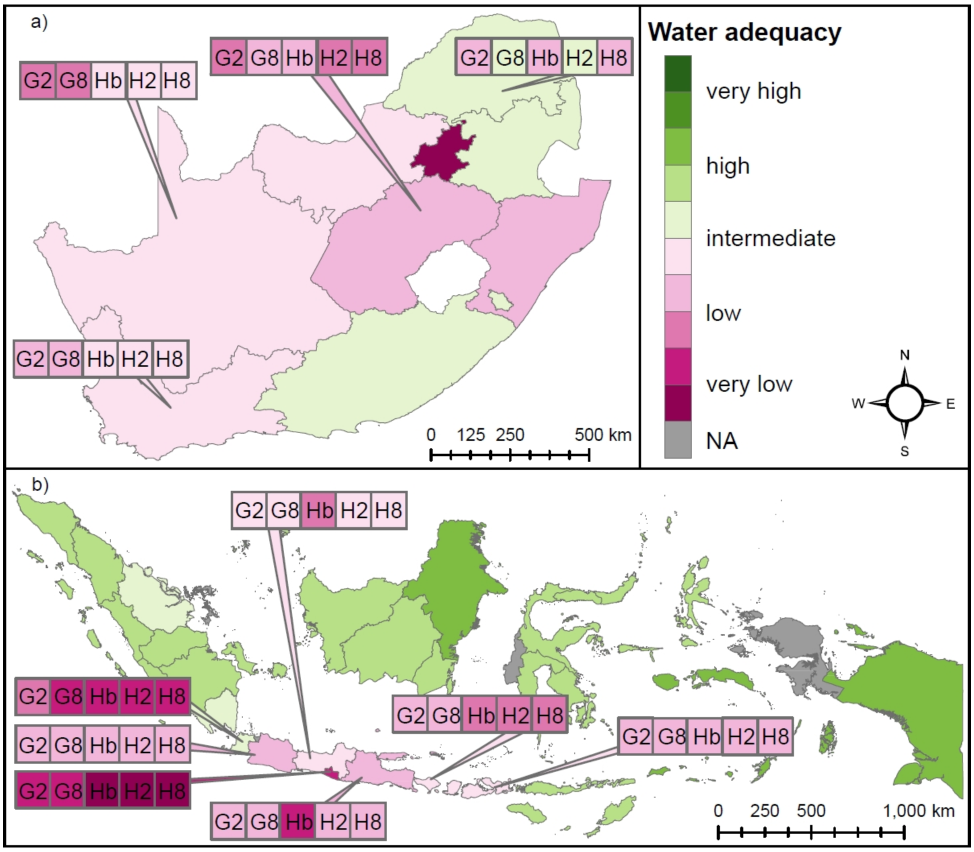

Figure 4.4: The maps show the integrated measure of water adequacy under current conditions (GDFLbase) for a) South Africa and b) Indonesia. Colored boxes show changes in water adequacy where these occur, differentiating the models and RCPs. G2: GDFL2.6, G8: GDFL8.5, Hb: HADbase, H2: HAD2.6 and H8: HAD8.5.

Figure 4.4 shows the integrated water adequacy (all_adequacy) for South Africa and Indonesia for current conditions, as well as future changes where applicable. In both countries, regions of lowest adequacy are those with the highest population density (depicted in Fig. 4.1). Projected changes in water availability do not affect the overall adequacy of water for human use in most regions, as quality and access play such an important role, however changes are apparent in some regions. Here, also differences between the two applied models become visible. Population density plays a crucial role in determining the adequacy of water availability (all_water). A large number of users may lead to overall scarcity, either due to resource limitations or quality restrictions. In the example countries, regions with high population density are currently close to the thresholds of water scarcity and population growth is likely to aggravate the situation. The projections of future water availability project only marginal changes in overall water resource availability in both countries and in several regions, changes may lead to increases in water resources.

However, due to an increase in population, especially in already densely populated areas, per capita availability declines, leading to potential water scarcity.

In South Africa, mean overall adequacy (all_adequacy) is intermediate to low (GDFLbase: 0.41, HADbase: 0.4) and the highest values of adequacy also remain at intermediate levels with values between 0.51 and 0.55 in the regions of Eastern Cape, Mpumalanga and Limpopo. The water adequacy is most severely limited in Gauteng, with a very low adequacy of 0. Though generally resource availability under the current climate is very adequate in the regions of South Africa, municipal and industrial water quality are low to very low in many areas.

In Indonesia, water resources are generally abundant, but the metropolitan region of Jakarta faces some water limitation and projections of water availability show further reductions in the region. Though overall water availability is projected to increase in most regions, population growth in already populous areas of the country is also projected to increase significantly, keeping constant or diminishing per capita water availability.

The island of Java, for example, is home to the largest cities and shows the lowest values of water adequacy and a decrease in adequacy over the coming decades. Mean adequacy under current conditions in Indonesia is intermediate, with lowest values in the densely populated regions of Bali with intermediate to low water adequacy. Similarly, the regions of Central, East and West Java as well as Yogyakarta display low to very low values. Where adequacy is low under current conditions in Indonesia, further changes are projected, leading to additional reductions in water adequacy. Conditions are best in Maluku Islands, East Kalimantan and Papua, with high values across models and scenarios. Generally, access to an improved water source (m_access) is low to intermediate, leading to an overall reduced adequacy (m_adequacy). Water quality in Indonesia for all users is intermediate to high and water availability is high, except for the densely populated regions. As measures to increase the security of supply of water for irrigation purposes are relevant mainly where water shortages are to be expected, agricultural adequacy (a_adequacy) is high, despite a lack in irrigation equipment and low dam density in many regions. The security of supply indicator performs best in those regions, where water availability is below the scarcity threshold, allowing to buffer potential shortages in water resources.

3.1 Sectoral priorities of water adequacy

While an overall aggregate indicator of water adequacy gives important information on the overall situation of water security, a sectoral differentiation allows prioritizing especially stressed sectors to most efficiently improve water adequacy. Comparing the sectoral adequacy, it is apparent that the municipal as well as environmental water adequacy are lowest, in both South Africa and Indonesia, also showing the lowest spread between regions (Fig. 4.5). In Indonesia, municipal water adequacy is lowest in rural regions, where

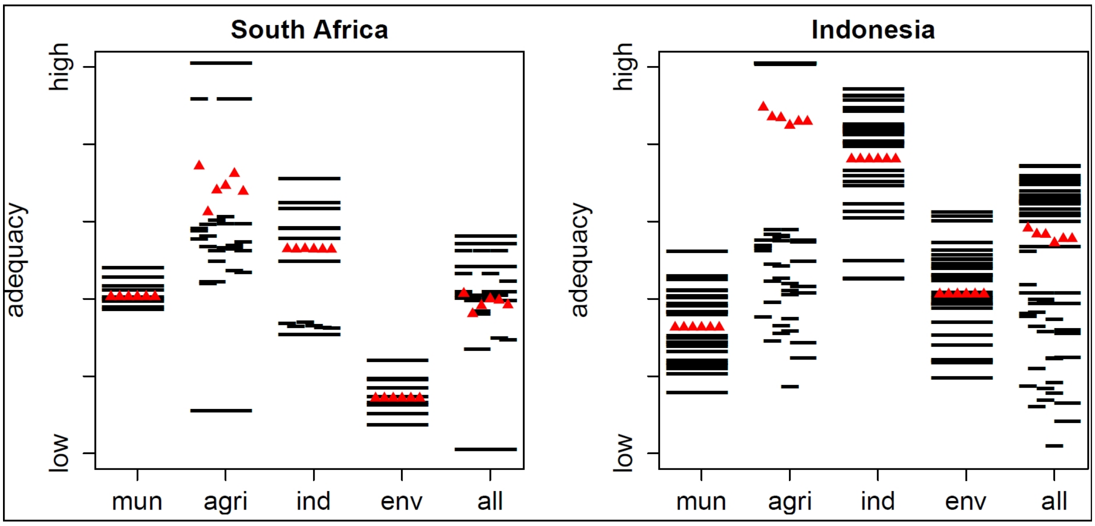

Figure 4.5: Sectoral water adequacy in South Africa (left) and Indonesia (right), showing results for the individual sectors (mun=municipal, agri=agricultural, ind=industrial, env=environmental, all=overall). Black lines show results for the individual municipalities, red triangles show the country average for results across models and RCPs from left to right: GDFLbase, GDFL2.6, GDFL8.5, HADbase, HAD2.6, HAD8.5.

especially the access to an improved water sources is limited. In several regions, environmental water quality dominates the result. In the most densely populated regions of Bali as well as East and West Java, the overall water availability proves to be a limitation under future conditions.

Agricultural water adequacy shows the highest spread across regions in both countries. While the mean adequacy is intermediate to high in both countries, some regions are severely water constrained. When looking at the overall adequacy of the three different sectors municipal, industrial and agricultural, the analysis shows that for the municipal and industrial sectors the main impediment are water quality and access factors, rather than the availability of water resources. This also holds for short term future scenarios. In the case of agricultural water resources, however, the availability of sufficient irrigation water plays a role in some regions of the case study countries.

Identifying the sectors and factors most relevant for each region in determining the adequacy of water resources provides important information to improve the quality of water resources and access in an efficient way. Fig. 4.6 shows which sectors most severely constrains water adequacy in each region. Where this factor changes over time, this is indicated by a box in the respective colour. In the case of South Africa, environmental water adequacy is a severe constraint for all regions and has the strongest influence on the overall result. The map therefore shows the second-most limiting factor. Environmental water conditions for the regions of Indonesia are also often low and follow as second-most limiting factors for all regions.

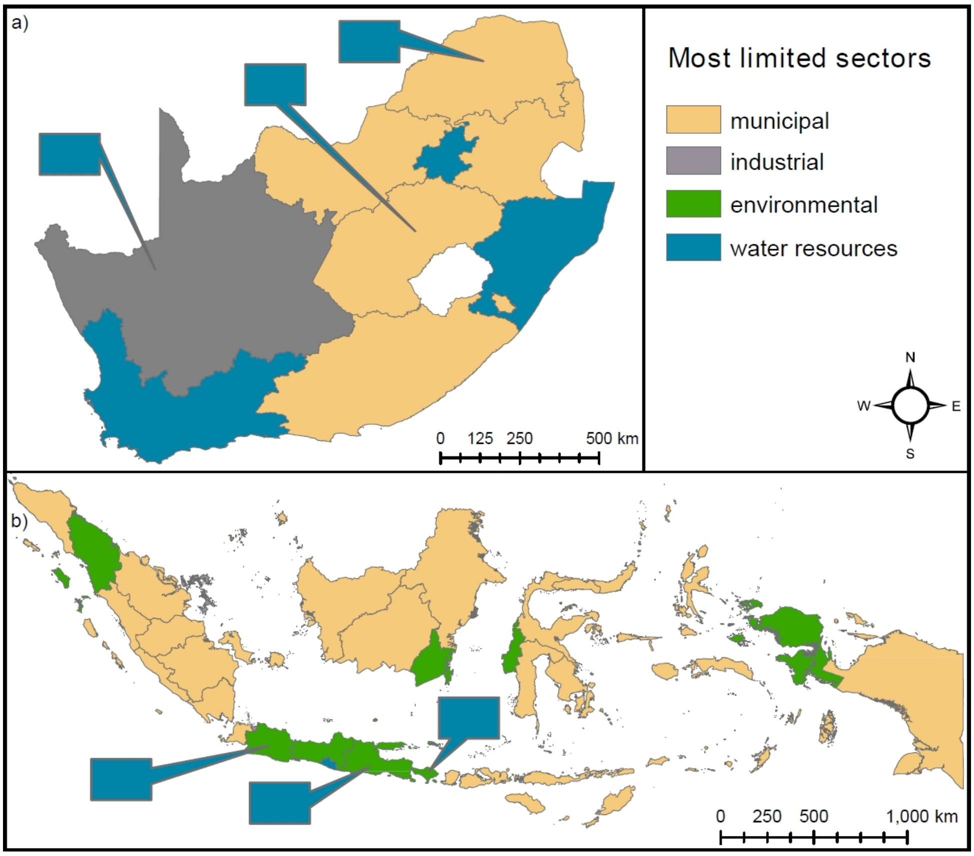

Figure 4.6: Overview of the most limited sectoral adequacy for the regions of a) South Africa and b) Indonesia. Where changes occur across scenarios, these are indicated by a box in the respective colour. Note that the sectoral limitations shown for South Africa are the second-most important after the environmental sector.

In the case of South Africa, the results in the majority of regions are dominated by limitations in municipal water adequacy, when environmental constraints are not taken into account, except for the region of Gauteng, where water resources limit the results. However here, municipal water quality plays a much more important role than access. Similar to the findings in Indonesia, high population density (see Fig. 4.1), leads to limitations in water resources availability (all_water), in South Africa, especially under future conditions. The regions of Western Cape and KwaZulu-Natal are water limited under all scenarios, and water limitations are expected in Northern Cape, Free State and Limpopo in the future. The largest province of Northern Cape is a sparsely populated region, where mining is a predominant activity. Here, the industrial water quality is the most decisive factor for adequacy under current conditions.

4 Discussion

Our results highlight that sector-specific water needs are diverse and that several distinct factors determine whether the quality, quantity and access to resources are adequate. Calculating water adequacy for two case study countries, the present work exemplifies how such an integrated approach can be applied. Changing resource availability as well as population increases have an impact on the patterns of water adequacy. For effective and informed decision-making it is essential to provide detailed and applicable information on the sectoral differences which affect the adequacy of water resources.

The results of the analysis clearly show that infrastructure (municipal access and security of supply) and quality aspects play an important role to determine water adequacy. Though insufficient water resources, also over the course of the next decades, have an impact in some regions, often the distribution of population plays an important role, as densely populated places face more severe water scarcity.

In some of the analysis regions, agricultural water is already limited. In Indonesia, for example, most agricultural production currently takes place on the densely populated island of Java. Here, water resources are already limited and population growth in this region may aggravate the problem. Reduced water availability in the future may affect domestic food security, if water resources available become insufficient in relevant growth phases and supply infrastructure is insufficient to meet additional demand. Even today, Indonesia is a net importer of food and malnutrition and stunting among children is present (WFP, 2012). With increasing development and higher demand lifestyles, the water-intensity of food consumption patterns may increase, further exacerbating the problem (Pradhan et al., 2013).

Our findings show that in Indonesia, the security of supply indicator is usually adequate in regions, where water availability is below the threshold, implying that awareness of shortages is present and potential scarcity can be buffered to some extent. Contrary to this, in South Africa buffering infrastructure in the from of irrigation equipment and dams is inadequate in the whole country, leading to low agricultural adequacy in some regions. Due to the current low per capita water use ($284\,\mathrm{m}^3/\mathrm{cap}^{-1}/\mathrm{yr}^{-1}$ (FAO, 2005)), water demand remains below available supply, therefore the overall water availability is currently not the main limitation to water access. Rather, inadequate supply infrastructure and lacking quality are an important impediment to adequate water (IRIN, 2009; Muller et al., 2009), which is also visible in our results. Though water is scarce in some regions, South Africa is currently a net food exporter. However with a trend towards more water intensive lifestyles, water demand is expected to overtake supply in the coming years, which may lead to competitions between sectors.

Currently, water use in both example countries is below the minimum requirement identified in the literature (Table 4.1) (Indonesia: $531\,\mathrm{m}^3/\mathrm{cap}^{-1}/\mathrm{yr}^{-1}$ (FAO, 2011), South Africa see above). Increasing development may lead to additional pressured here, as lifestyles adjust to prevailing patterns in highly developed countries and water use increases. Improved access to water resources for example, which is urgently needed in many regions of the case study countries, has been shown to increase water consumption, as more water is used e.g for hygiene purposes, an important improvement to heath status (Larson et al., 2006). Our results show, that water is a limiting factor in some densely populated regions already today. Here, growing water demand would indeed be critical. Especially in regions where high population growth and high development is expected, integrated water management schemes may therefore become increasingly important. The projections of climate impacts on water resources in the present analysis focus on a short-term future scenario until 2030. Projected changes in water resource availability are not pronounced at this timescale, but changes in population are the main driver of reductions in per capita water availability.

Limitations in water quality play a very decisive role in both countries and in all sectors. Especially the environmental water adequacy proves to be one of the most limiting factors for water security/adequacy, due to increasing threats to biodiversity from high pollution levels. Even when prioritizing environmental water needs, as has been done in the present approach by allocating environmental water needs before other sectors, water quality threatens environmental water sustainability. Where access to drinking water is not provided through improved sources, high pollution levels may also have direct health implications. Additionally, low quality water for agriculture may also lead to reduced yields or health effects due to contaminated foods (Toze, 2006). Sustainable adaptation and development in the water sector should concentrate on improving water infrastructure and on improving the quality of accessible water in many regions. Improving infrastructure can also reduce the susceptibility to impacts of climate extremes, as contamination and disruption of water infrastructure then becomes less likely.

The presented approach was developed to be applicable in developing countries, enabling comparability between regions. It provides an overview of the main determinants of water adequacy and is applied in a first exemplary approach, using comparable data for two case study countries. In its present form, the approach has some limitations. By using global data sets for example, comparable results between countries are produced, however, regionally collected data may reflect regional to local conditions more accurately. To reconcile the goal of comparable analyses with more detailed accounts of regional specificities, further analyses of local conditions could provide additional details, providing a more comprehensive picture. A regional to local implementations of the methodology could also take into account local characteristics, such as water intensive industries and energy production types, providing further detail on locally-specific limitations to sectoral water adequacy. This would also allow to include the knowledge of regional experts, through participatory approaches. The sectoral allocation of water needs currently addresses potential water requirements, rather than water use or withdrawal. Consequently, water used by one sector is assumed to be unavailable for other purposes. Including a more process-based view of water use, also accounting for the potential for successive use water resources between sectors would provide an additional improvement of the approach.

Additionally, variations in water requirements could be taken into account in a localized application of the approach. This could include differences according to the specific regional distribution of production patterns, for example, as well as changes resulting from expected future development. Further, seasonal variations in water availability play an important role at the local and regional scales, but have not been included in the present application. Especially for agricultural production, seasonal variations in precipitation and water availability play an important role in determining water adequacy. In order to be applicable as a tool for locally-specific decisions on water management, further refinement of the specific regional priorities would be needed. For the present implementation, we chose to rely on generic and generally valid assumptions on water requirements. Detailed assessment of the prevailing local requirements would be an important improvement of the approach. Finally, the forecasting capacity of the results with regard to future developments is limited, as the quality and infrastructural components could not be calculated with scenario values in a comparable way, as data were unavailable at present.

The fact that infrastructure, access and quality are often more important than water availability itself in determining adequate water availability, especially in developing countries, is widely recognized (Rijsberman, 2006). However, quantifications to identify the most pressing factors on a sub-regional scale have so far been lacking. The presented approach outlines a novel way of providing comparable results across regions to identify, which aspects of water supply need to be improved most urgently. The approach can point towards adaptation strategies which allow prioritizing between different development goals and choosing strategies, which most efficiently improve water availability. The approach allows testing different allocation patterns for different water sectors and can show at which point overall water adequacy could be most efficiently increased by adjusting single factors of the analysis.

As water resources become scarce, either due to increasing population and demand, or through a reduction in resource availability, competition between different sectors to have access to sufficient water resource may arise. The present approach allows to identify needs of different users and make visible, which aspects are important in different regions. By taking into account sector-specific needs, the approach can provide management relevant information for decision-makers. It also allows identifying potential trade-offs and competitions between sectors.

5 Conclusions

This paper presents an integrated approach to determine how important sectors are adequately supplied with water. The applied fuzzy logic algorithm allows the identification of regions with inadequate water supply in a comparable way. The approach also allows identifying those factors and sectors which are most important in a regional context, contributing to decision-making processes for sustainable development and integrated climate change adaptation. It is clear that water scarcity is essentially human made and population density, infrastructure and associated pollution determine whether available water is sufficient and in adequate form to be used. Continued population growth, coupled with increases in per capita water consumption are important determinants of reductions in water adequacy. In the present short-term future scenario, climate change has little influence on the reduction in water availability, though towards the end of the century, this may pose additional pressures in water resources. It is essential to increase knowledge of processes which determine adequate water availability, as access to sufficient clean water is the most critical of human needs. Thus, improving access to water has high priority, especially in developing countries, where development and human well-being are often severely restricted by lacking water access. Applicable approaches, which combine a range of determinants of water adequacy and allow to prioritize interventions are urgently needed to advance sustainable development. The presented approach is an important contribution to improve knowledge and cope with the multiple challenges the water sector faces.

5

Towards sectoral and standardised vulnerability assessments: the example of heatwave impacts on human health

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Abstract

The relevance of climate change is especially apparent through the impacts it has on natural and societal systems. A standardised methodology to assess these impacts in order to produce comparable results is still lacking. We propose a semi-quantitative approach to calculate vulnerability to climate change, with the ability to capture complex mechanisms in the human-environmental system. The key mechanisms are delineated and translated into a deterministic graph (impact chain). A fuzzy logic algorithm is then applied to address uncertainty regarding the definition of clear threshold values. We exemplify our approach by analysing the direct impacts of climate change on human health in North Rhine-Westphalia, Germany, where the urban heat island potential, the percentage of elderly population as well as the occurrence of heat waves determine impact intensity. Increases in heatwaves and elderly population will aggravate the impacts. While the influence of climatic changes is apparent on larger spatial scales, societal factors determine the small scale distribution of impacts within our regional case study. In addition to identifying climate change impact hot spots, the structured approach of the impact chain and the methodology of aggregation enable to infer from the results back to the main constituents of vulnerability. Thus, it can provide a basis for decision-makers to set priorities for specific adaptation measures within the complex field of climate change impacts.

1 Introduction

The relevance of climate change for humankind is revealed through the impacts it has on natural and societal systems. The severity of these impacts depends on a variety of factors, which are critically dependent on the specific properties of a given system or sector. To address the context specific impacts of climate change, impact and vulnerability assessment methodologies have been developed. The Intergovernmental Panel on Climate Change has provided an encompassing definition of vulnerability, aiming to incorporate the specific properties of the systems under analysis through considering that sectors react differently to climatic stimuli, and have different capacities to withstand adverse effects of accelerated climate change (Adger et al., 2007; IPCC, 2007b). Conceptually, vulnerability is a powerful concept, as it aims to consider the whole continuum of possible impacts and allows to delineate comparable situations. However, the concept is weak in terms of its mathematical foundations. A general methodology that allows a standardised assessment and produces comparable results is still lacking (see e.g. Ionescu et al., 2008; Füssel and Klein, 2006). Consequently vast numbers of impact and vulnerability studies exist which employ diverse methodologies and produce inconsistent results.

Comparable small-scale vulnerability assessments, however, are a precondition for identifying regional hot-spots and for prioritizing adaptation to efficiently allocate available funds (Adger et al., 2007; Carter et al., 2007). These assessments have to consider the interdependencies involved while being as simple as possible in order to deliver tangible results to decision-makers and provide transferability to other regions. An understanding of the cause-and-effect chains that govern the processes that lead to a situation of vulnerability is essential. Some singular properties of a system may only lead to negative impacts if they occur in specific socio-economic settings. Thus a focus of the interrelations between climatic and socio-economic variables should be a central point in any analysis of impacts and vulnerability. Certain properties of a system may render it more vulnerable. Their spatial concomitance further increases the risk of adverse effects. Thus, the spatially explicit depiction of properties and processes is expedient.

The present article proposes a semi-quantitative synoptic approach which is developed closely to concrete climate related problem complexes, thus relating to the reality decision-makers are facing. A qualitative description of the climatic sensitivities of a given sector delineates the key mechanisms relevant within the analysis context. These are derived from literature as well as from plausible expert knowledge. Subsequently, these mechanisms are translated into a deterministic graph (impact chain), which describes critical elements determining impacts and vulnerability. This systematic conceptualization reduces highly complex systems to the relevant cause-and-effect relationships. To quantify this qualitative representation, indicators are derived. A fuzzy logic algorithm is applied to master the challenges posed by uncertainty and context-specific unclarity. We will exemplify the proposed approach by analysing the direct impacts of climate change on human health for the administrative level of municipalities in the study region of North Rhine-Westphalia (NRW), Germany.

Many similar and overlapping definitions and concepts to describe and assess how systems can adversely be affected by natural hazards have emerged from different schools of research (see e.g. Birkmann, 2006; Adger, 2006; Brooks, 2003; Miller et al., 2010). For our analysis we draw on the vulnerability framework provided by the IPCC, where it is defined as *"the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity."*(IPCC, 2007b). We thus see vulnerability as resulting from the specific properties of the system under analysis, which determine its sensitivity to a hazard that it is exposed to. Following the nomenclature introduced by Füssel (2007), we examine the impacts on human health *(attribute of concern)* due to heat stress *(exposure)* in the context of climate change *(temporal reference).*

Various studies have been carried out that clearly relate increased mortality and morbidity rates to above normal temperature (Laschewski and Jendritzky, 2002; Havenith, 2005; Kovats and Kristie, 2006; Hajat et al., 2007; Menne and Ebi, 2006; Baccini et al., 2008). These analyses are often motivated by concrete events such as the Chicago heatwave in 1995 (Klinenberg, 2002; Semenza et al., 1996) or the European heatwave in 2003, with approx. 40.000 excess deaths over Europe and highest mortality rates in older age groups (see e.g. Borrell et al., 2006; Kosatsky, 2005; Vandentorren and Empereur-Bissonnet, 2005; Rebetez et al., 2006). Beside higher age also the duration and intensity of a period with heat stress (Huynen et al., 2001; Kysely, 2004) or the urban structure (Upmanis and Chen, 1999; Eliasson and Upmanis, 2000) contribute to above normal mortality rates. The causal relations between specific attributes and impacts of heat stress are thus well established. Less attention has been given to concepts and methods to depict the spatial occurrence of these attributes. While it has been recognized that an increase in temperature extremes is likely over the course of the century, and that climate change may be a threat to human health in the future (Costello et al., 2009), only few approaches assess possible future risks to human health (Vescovi et al., 2005; Meyer et al., 2009).

Through the underlying impact chain and the translation of these cause-and-effect chains into a fuzzy logic based decision tree, our approach provides several improvements relative to similar approaches presented by Vescovi et al. (2005) and Meyer et al. (2009). On the one hand the use of fuzzy logic allows the consideration of uncertainty, both stemming from data as well as from the use of scenarios. More importantly, we clearly relate the analysis to the cause-and-effect relationships that define the impact. The approach allows to identify those factors most relevant for the smallest unit of analysis, thus giving indications on how to most effectively cope with vulnerable situations. Previous approaches, such as the integrated neural networks approach by Kropp et al. (2006), aggregate sectoral impacts in such a way that underlying processes become unidentifiable from the results. While they depict impact hot-spots, response options become blurred. Our methodology retains the important properties, thus providing indication towards effective adaptation.

We outline the pertinent features of our approach in the following pages and have organised this article as follows. After a short overview of the study region in Section 2 the methods and the input data sets are described in Section 3. The resulting distribution of impacts is presented in Section 4 while Section 5 discusses the results achieved in details, followed by a conclusion in Section 6.

2 Study site

The state of North Rhine-Westphalia (NRW) is situated in the north-west of Germany and comprises 396 municipalities (Figure 5.1). With a population of 18 millions (2008) and an average population density of over 500 cap/km^2 NRW is the most populous and at the same time most densely populated state in Germany. Regional characteristics are quite diverse in terms of climate and geomorphology. Two main types of landscape can be found in NRW, namely the North German Lowlands with elevations just a few meters above sea level and the northern German Low Mountain Range with elevations of up to 850m. The lowlands comprise the Rhine-Ruhr Area which is one of the largest metropolitan areas in Europe with a population of approx. 10 million and very high population density of 2.100 cap/km^2. Opposed to this, in the mountain regions population density is rather low with 150 cap/km^2. NRW contributes over 20% of the overall German GDP (2008) (DESTATIS, 2009). The above mentioned two main landscape types are also distinguishable in the climatic characteristics of the region: Annual mean temperature amounts to around 10 °C (1961-1990)[1] in the lowlands and about 5 °C in the mountain regions. This spatial variation is also reflected in the occurrence of temperature extremes, both in terms of frequency and intensity. Yearly mean precipitation of up to 1.500 mm has been recorded in higher elevations, while the Rhine valley received a mean sum of 620 mm per year.

Demographic change towards an elderly population is apparent in NRW; in the year 2008, 19% of the population were over 65 years old and an increase up to 29% is expected until 2030 (IT.NRW, 2010).

[1]Measured temperature and precipition values for the baseline period as provided in the regional climate model STAR (Werner and Gerstengarbe, 1997; Orlowsky et al., 2008)

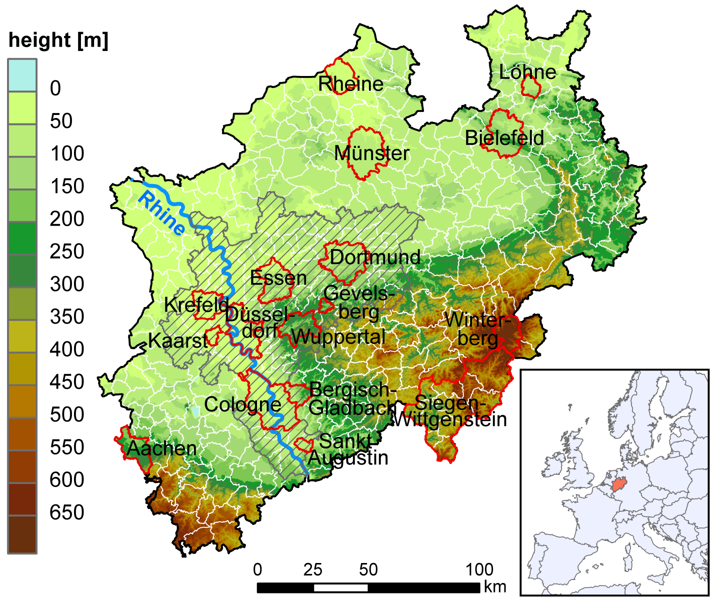

Figure 5.1: The study region North Rhine-Westphalia and its location within the European Union (Municipalities discussed in Sect. 4 and 5 are marked red, the metropolitan region is delineated in grey)

3 Methods and data

3.1 The concept of impact chains

The term 'impact chain' describes the systematic depiction of the processes triggered within a given system deriving from a (climate) stimulus. The structured approach allows for a conceptualized visualization of the complex interrelations found in coupled human-environmental systems. The focus lies on the effects a certain climatic stimulus has on the system and how this effect propagates through the system, depending on its inherent characteristics, which in turn influence the severity of the impacts.

A systematic literature review provides information of these properties, including reaction, processes and feedbacks between important elements (see e.g. for similar methods Geist and Lambin, 2004, 2002). This information is translated into a stylized representation by means of a directed graph, clearly describing the impacts deriving from a specific climate stimulus (upper part of Figure 5.2). Each node of the graph describes a key element of the system, while the edges represent the nature of their interaction. This impact chain comprises only those elements that critically determine the impacts and can be attributed with a measurement. The elements of the impact chain are translated into quantifiable indicators and aggregated with operators to derive an integrated measure of impacts and vulnerability (lower part of Figure 5.2). Corresponding to the definition of vulnerability given in the introduction, the climate stimulus represents the hazard that the system of analysis is exposed to (exposure). The system properties describe the socio-economic setting that may aggravate or relieve the pressure that the system is exposed to (sensitivity, adaptive capacity). The impact chain thus depicts how impacts related to a climate stimulus propagate through the system, with the vulnerability critically determined by the system properties.

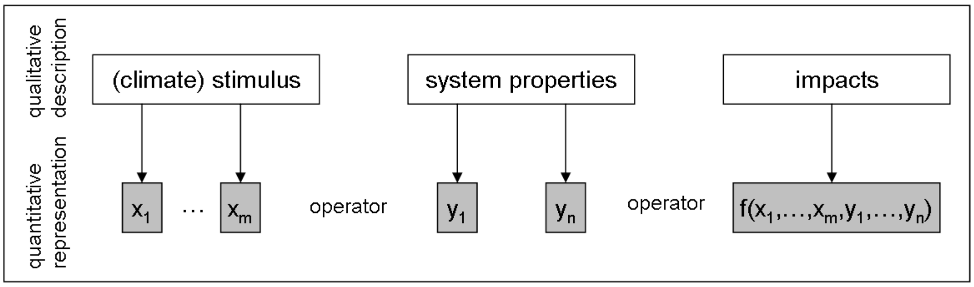

Figure 5.2: Schematic overview of the impact chain approach: the systematic qualitative description contains influences, causes and effects for a specific system; these are quantitatively represented by indicators (x, y) and aggregated through operators

From the manifold impacts deriving from heat waves we choose the system 'human health' to demonstrate the approach and develop an impact methodology. The direct impact of interest is the increase of morbidity as well as mortality rates under conditions of heat extremes. For this, the following key factors are relevant (presented in the order of the subsequent analysis, see Figure 5.3):

- Regional and local air temperature and resulting heat stress is not determined by atmospheric processes alone, but urban areas can significantly alter regional climate patterns through the formation of an urban heat island (UHI) (Oke, 1982; Kuttler, 2008). Due to the specific heat absorption, retention and conduction capacities of urban materials urban temperature can be $5 - 11\,°C$ higher than surrounding areas (see e.g. Oke, 1973; Matzarakis, 2001; Stathopoulou and Cartalis, 2007; Kuttler, 2008; Hupfer and Kuttler, 2005). Further, reduced plant cover decreases the evaporative cooling capacities of cities. This temperature gradient is especially pronounced just after nightfall (Matzarakis, 2001). The proportion of sealed surfaces is one important contributing factor favouring the formation of a UHI.

- Additionally, the height of buildings can further increase the UHI as the surface area for heat retention is increased (Hupfer and Kuttler, 2005; Matzarakis and Mayer, 2008) and more radiation is trapped between buildings (Arnfield, 2003; Kuttler, 2008). Population density can be used as proxy variable to indicate the degree of urbanity and corresponding higher residential houses. This has the additional value of only including those areas into the assessment where many people are at risk.

- The UHI plays a critical role in exacerbating heat stress (Koppe et al., 2004; Koppe, 2005; Mavrogianni et al., 2009), since high temperatures are increased at all times of day, while nighttime cooling is reduced (Kovats and Hajat, 2008).

- Extremely high temperatures are clearly associated with significantly increased mortality and morbidity rates (Semenza et al., 1996, 1999; Kosatsky, 2005; Vandentorren and Empereur-Bissonnet, 2005). The additional heat load may overexert the cardiovascular system in particular for the elderly people (Wainwright et al., 1999; Hodgkinson et al., 2003). Consequently, there is a clear correlation between a mortality increase in population aged 65 or older (population $\geq$ 65) and periods of extremely high temperatures (Huynen et al., 2001; Laschewski and Jendritzky, 2002; Kovats and Kristie, 2006). The proportion of this age group can thus indicate a higher regional sensitivity towards the impacts of heat waves.
- As definitions of heat waves are context and location dependent, we use a regional definition, applicable for temperate climate regions such as NRW. Here, periods of at least three consecutive days with maximum temperatures (Tmax) $\geq 30\,°C$ correlate with significantly increased mortality and morbidity rates, especially in age groups of 65 years or older (Huynen et al., 2001; Kysely, 2004). Consequently, a heat wave for the purpose of this study is defined as a period of at least three consecutive days with Tmax $\geq 30\,°C$. All days constituting a heat wave are further referred to as heat wave days (HWD).

Thus, the sensitivity of a region to be negatively impacted by heat waves can be delineated by two spatially resolved key factors, namely the potential intensity of the UHI (potential UHI), represented by the sealed surface area and the population density, as well as the proportion of population $\geq$ 65. Where all of these occur in conjunction a significantly augmented regional sensitivity has to be expected. To finally describe regional impacts, the regional number of HWD as a measure of exposure is combined with the previously aggregated measure of sensitivity.

3.2 Data

We selected spatially resolved data, which are easily accessible and useful to indicate the above described processes. The data includes the percentage of sealed surfaces, population density, the proportion of population $\geq$ 65 and the number of HWD. The analysis is performed for a baseline period (1961-1990) and a scenario period (2031-2060) with a spatial resolution of the 396 municipalities. Sociogeographic data from the Statistical Agency NRW (Landesbetrieb für Information und Technik Nordrhein-Westfalen, IT.NRW) is available for all determinants of sensitivity. The sealed surface area is represented by the proportion of settlement and traffic area per municipality as proxy, as this can sufficiently represent the surface properties favouring a UHI development (Meinel and Hernig, 2005). We compared this dataset to the Authorative Topographic-Cartographic Information System (ATKIS) landuse classification and found only slight variations. Therefore either dataset was considered equally suitable for the analysis; we chose data provided by IT.NRW to ensure consistency across the used datasets. There are currently no future projections for sealed surface area and past developments show no clear trends that can be extrapolated into the future. Therefore most recent values of 2008 are introduced for both analysis time frames. Data on the percentage of population ≥ 65 per municipality is retrievable for the year 2008 (baseline period) as well as for a projection to 2030 (scenario period).

Two regional climate models, CCLM and STAR, were applied to estimate the number of HWD for the baseline and scenario period considering a forcing according to the emission scenario A1B (Nakićenović et al., 2000). The CCLM model is a full-dynamic and non-hydrostatic unified weather forecast and regional climate model with a grid size of 0.2 degrees (Lautenschlager et al., 2009), nested into the General Circulation Model (GCM) ECHAM 5/MPI-OM (Roeckner et al., 2003). The model STAR is a statistical model based on temperature trends from the same GCM, but considering statistical features from empirical measures from 1951 to 2003 which are re-sampled using cluster analysis to provide scenario data up to 2060 (Werner and Gerstengarbe, 1997; Orlowsky et al., 2008). We extracted the number of days from both models which are part of at least three consecutive days with Tmax $\geq 30\,°C$. The data from the STAR model is provided for 244 stations across NRW and was spatially interpolated by inverse distance weighing. To approximate the number of heat waves per municipality we used the yearly mean over the 30-year periods of all values within the respective polygon for each model and assigned to respective number to the polygon for the analysis.

3.3 The fuzzy logic algorithm to calculate heat wave impacts

The structural composition of our analysis approach is motivated by the elements of the identified impact chain (Section 3.1). The translation of these into a quantifiable methodological framework poses several challenges, such as inconsistent units and uncertainties from scenarios and projections. Moreover, boolean-type either-or decision rules are difficult to apply within qualitative contexts, where gradual membership to classes may be needed. Fuzzy reasoning provides a means to approach these challenges (for details see e.g. Zimmermann, 2001; Zadeh, 1965; Kropp et al., 2001). The first step of any fuzzy analysis is the fuzzyfication of the base variables of the system with respect to defined logical clause (lingustic categories). A function to define the degree of membership to linguistic categories, such as *high* or *low* is then defined for each of the base variables. These categories relate to the analysis context, in our case to health related risks for humans.

Upper and lower thresholds for membership (ι_1, ι_2) are defined to calculate continuous degrees of membership through Equation 5.1.

$$\mu_{zi}(\iota) = \begin{cases} 0, & \iota \leq \iota_1 \\ \frac{\iota - \iota_1}{\iota_1 - \iota_2}, & \iota_1 < \iota < \iota_2 \\ 1, & \iota_2 \leq \iota \end{cases} \tag{5.1}$$

$$\text{with} \quad \iota_1 < \iota_2$$

Fuzzified datasets take values between 0 and 1, with a value of 1 indicating full membership to the linguistic variable. Subsequently, the datasets are combined using fuzzy operators, such as a FUZZY_OR ($\vee$) (MAX) or FUZZY_AND ($\wedge$) (MIN). Unlike the strict application of boolean MIN or MAX operators, fuzzy operators allow for compensation through a γ-value, which can take values between 0 and 1 (Equation 5.2).

$$\mu(z_1 \wedge z_2 \wedge \ldots \wedge z_n) = \gamma * \min(\mu_{z1}, \mu_{z2}, \ldots, \mu_{zn}) + (1-\gamma) * \frac{1}{N}\sum_{i=1}^{N} \mu_{zi} \tag{5.2}$$

The introduction of γ results in the consideration of the arithmetic mean of all input values to some extent, thus diluting the strict application of the operator to the extent of γ, with values near to 1 resulting in a rather strict application of the operator and values near 0 introducing significant compensation. To aggregate the variables that determine the impacts within our study we use a decision tree, which is structured according to the insights from the impact chain (Figure 5.3).

The heating effect of different surfaces can be clearly distinguished on building block scale (Lo et al., 1997; Stathopoulou et al., 2004) and sealed areas of minor extent can alter the local temperature regime significantly (Matzarakis, 2001; Hupfer and Kuttler, 2005). The regional mean of sealed surface area for NRW lies at 22% of the total surface. The German mean is currently at approx. 12.5%. To account for this local heating effect of sealed surfaces of minor extent we chose a lower value of 12.5% and an upper threshold value of 40% to define membership to the linguistic variable $\mu\left(\substack{\text{sealed surface area} \\ \text{high}}\right)$. Population density as a measure of urbanity is in use in many regions with values ranging from up 4 000 cap/km^2 (Japan) to 200 cap/km^2 (Australia). Thus regional differences are substantial and the local characteristics play an important role. We chose a lower threshold of 250 cap/km^2, corresponding to the German average and an upper threshold of 1 000 cap/km^2, corresponding to twice the regional mean in NRW to calculate membership to $\mu\left(\substack{\text{population density} \\ \text{high}}\right)$ as these thresholds can best describe the spatial variations of population density within the study region.

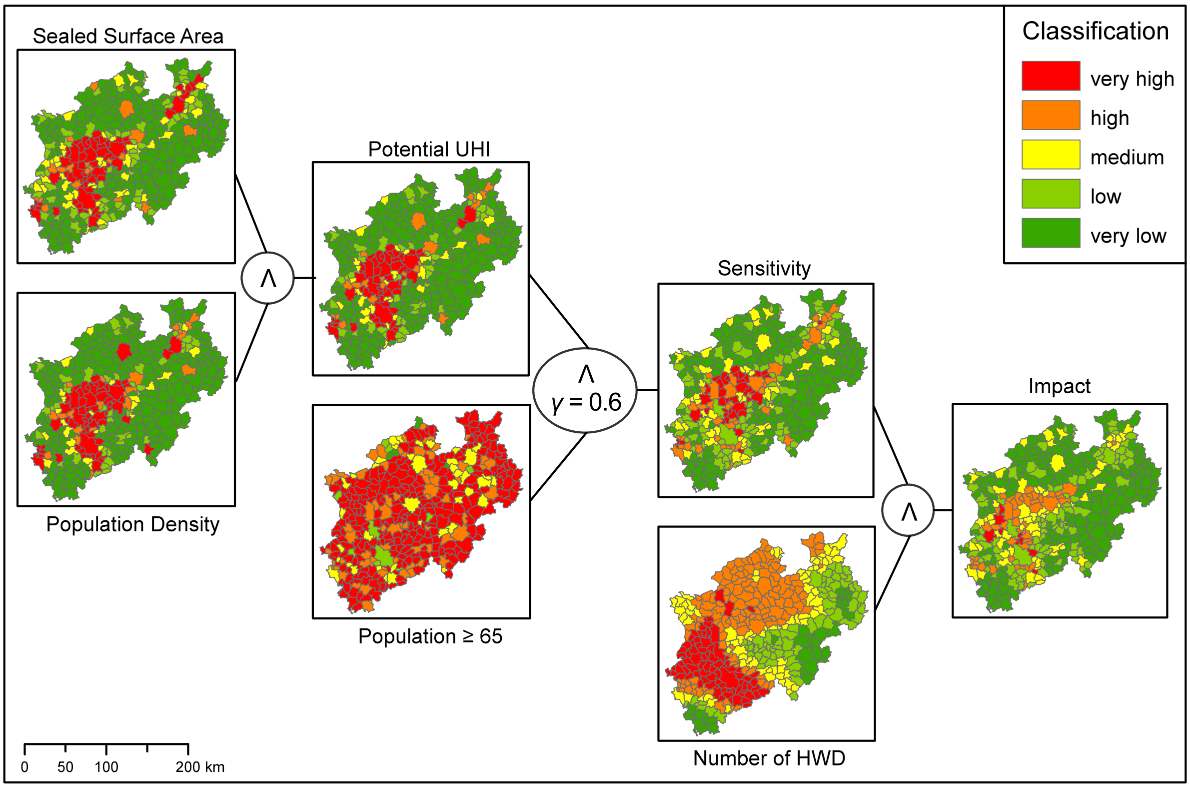

Figure 5.3: Fuzzy-logic based decision tree to assess the impacts of heat waves on human health; all maps show the fuzzified data; derived maps present the results obtained using climate data from the model STAR

We derive a measure for potential UHI intensity via the logical clause

$$\mu\binom{\text{sealed surface area}}{\text{high}} \wedge \mu\binom{\text{population density}}{\text{high}} = \mu\binom{\text{potential UHI}}{\text{high}}$$

where $\wedge$ is applied as a strict AND operator. The proportion of sealed surface describes a physical property of a municipality to develop a UHI. Additionally, the degree of urbanity indicates a higher building density, which may augment the excess heat and point to where a substantial number of people are at risk. Therefore only if both variables are high, a high level of sensitivity can be assumed.

Different data sets for current and future analysis periods are available for the variable population ≥ 65. Therefore, threshold values were chosen to cover both datasets by setting the lower threshold at the average values for the baseline period and the upper one for the average value of projection period. Above average municipalities will be partly a member of the variable in all cases while at the same time those municipalities are well captured that experience an extreme increase in sensitive population groups. Lower and upper thresholds for the membership function $\mu\binom{\text{population} \geq 65}{\text{high}}$ are set to 19% and 29% respectively.

$$\mu\left(\substack{\text{potential UHI}\\ \text{high}}\right) \wedge \mu\left(\substack{\text{population} \geq 65\\ \text{high}}\right) = \mu\left(\substack{\text{sensitivity}\\ \text{high}}\right)$$

is the logical clause to represent the sensitivity of a municipality towards heat waves.

Here, we introduce a compensatory γ-value of 0.6 to account for the fact that population with no individual prior risk factors may be adversely affected by an intense UHI while the elderly are susceptible to heat stress without further intensification. The γ-value of 0.6 gives higher impact to the minimum factor, thus a concomitant occurrence of both factors renders a municipality more vulnerable, as the strongest impacts occur where the population has multiple sensitivities. Yet, negative impacts also occur where singular sensitivities are apparent (Luber and McGeehin, 2008; Basu, 2002), therefore 0.4 of the result value is compensated with the arithmetic mean of both variables.

Threshold values for the fuzzification of heat wave data were chosen analogous to the definition of heat waves applied in this analysis. The lower threshold for membership to $\mu\left(\substack{\text{number of HWD}\\ \text{high}}\right)$ of three consecutive heat wave days corresponds to at least one heat wave every year while the upper threshold of nine days per year corresponds to a yearly average of three heat waves or a heat wave of a very long duration. The upper threshold also accommodates the records of the heatwave summer of 2003, when the study region experienced an average of 10 HWD with negative consequences for human health (Hellmeier et al., 2007).

The use of a strict AND operator within the statement

$$\mu\left(\substack{\text{sensitivity}\\ \text{high}}\right) \wedge \mu\left(\substack{\text{number of HWD}\\ \text{high}}\right) = \mu\left(\substack{\text{impact}\\ \text{high}}\right)$$

aggregates all variables to the final measure of impacts.

Figure 5.4 illustrates the membership functions in this study.

4 Results

Under climate conditions as projected by the model STAR, the mean values of impacts for NRW municipalities amount to 0.33, while the mean impacts for CCLM are slightly higher(0.36). While overall impacts are higher with CCLM assumptions, however the increase in impacts in relation to the baseline period is higher for the STAR model with 0.3 (0.25 with CCLM). Table 5.1 summarizes the results for all municipalities for both models. Under assumptions of the STAR model 13% of all municipalities have high to very high impacts, 71% display low to very low impacts while the remaining 16% have a medium level of impacts. In contrast to that, the results for the CCLM model classify 19% of all municipalities as highly to very highly impacted. A proportion of 69% falls into the classes low and very low with the remaining 12% displaying medium impacts.

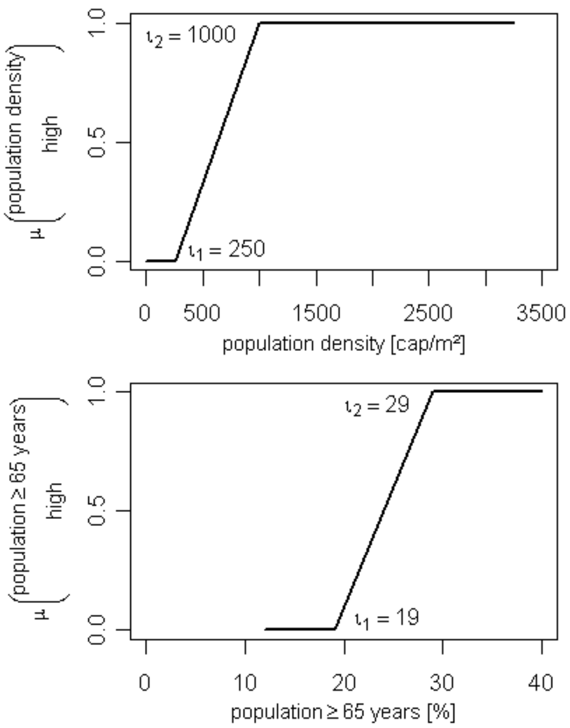

Figure 5.4: Threshold values ι_1 and ι_2 and corresponding ramps of fuzzy membership functions to fuzzify input variables for the decision tree; graphs cover the range of input values for each variable

Table 5.1: Number of municipalities corresponding to the five impact classes in the scenario period for the models STAR and CCLM. Impacts are classified from very low to very high, with equal class sizes of 0.2.

Vulnerability class	STAR	CCLM
Very high	9	37
High	47	41
Medium	61	47
Low	94	81
Very low	185	190

For a total of 274 municipalities the intensity of impacts is identical for both climate models; in 90 cases the results for the CCLM model are higher while in 32 cases the STAR model produces higher degrees of vulnerability. Altogether more municipalities are ranked as highly or very highly impacted under CCLM assumptions (78 municipalities). The smaller share of highly or very highly impacted municipalities under STAR (56 municipalities) correspond to those under CCLM except for one of the municipalities (Hagen), where impacts are projected under the model STAR and not under CCLM.

Our results show an overall increase in impacts over time, especially so in the densely populated Ruhr area and in parts of the Rhine valley (Fig 5.5). The spatial distribution of impacts as well as changes between the analysis periods show a distinct spatial pattern,

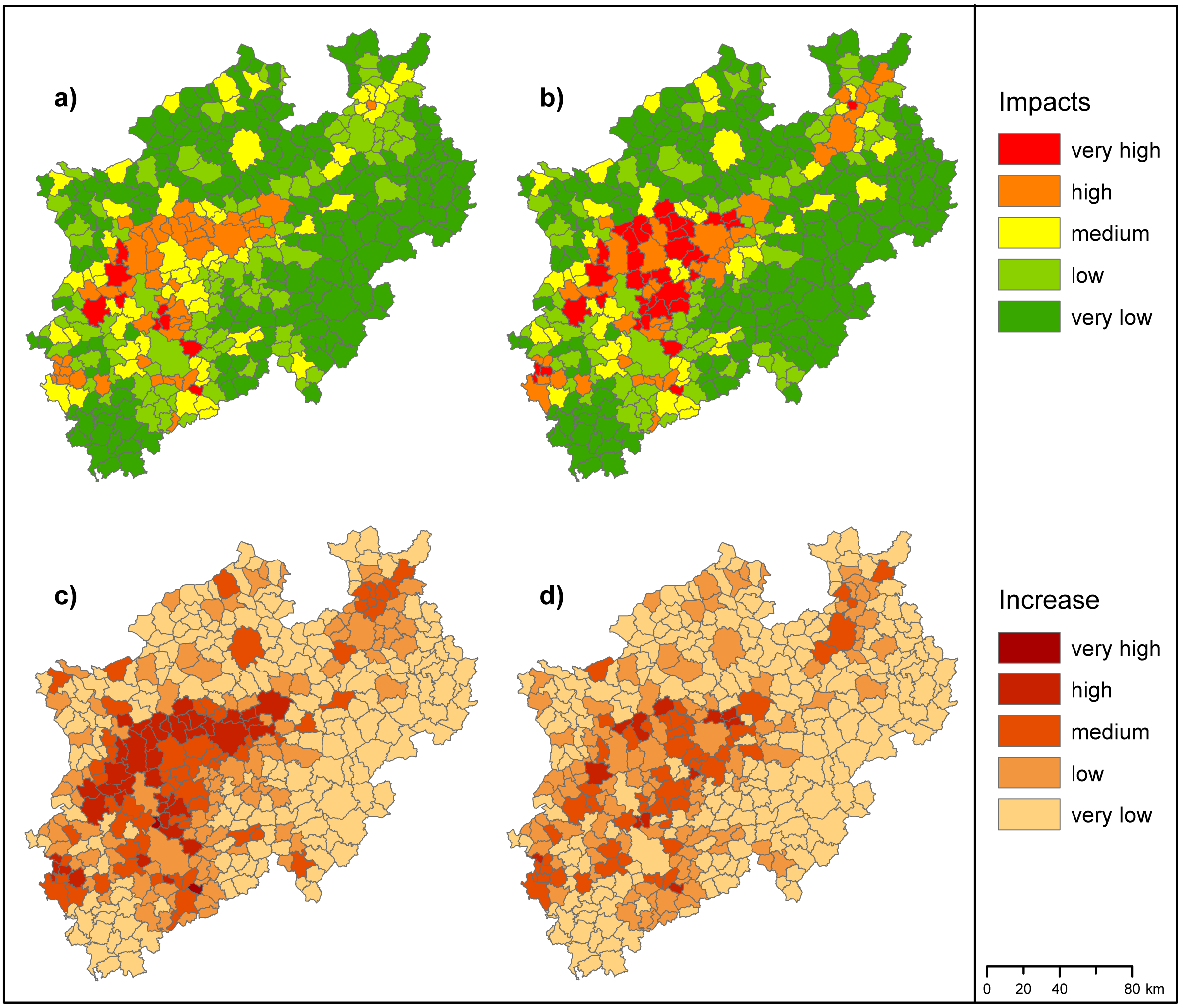

Figure 5.5: Impacts of heat waves on human health for the scenario period 2031-2060 for a) STAR and b) CCLM climate models and increase of impacts relative to the baseline period 1961-1990 for c) STAR and d) CCLM.

which is apparent in the results of both climate models. With some exceptions, low-lying and densely populated areas are most vulnerable. A general gradient of impacts is apparent from densely populated areas towards those less densely populated, with the mountainous regions displaying the lowest levels of impacts. The metropolitan region is distinguishable, with higher levels of impacts compared to surrounding areas, however the southern municipalities along the river Rhine are distinctly less affected. The large cities of Cologne and Düsseldorf, for example, though very densely populated, show low impacts.

Clusters of high to very high impacts emerge in the metropolitan Ruhr region, as well as in the North-East around the city of Bielefeld under both climate models. With exception of the city of Münster the northern lowlands exhibit very low levels of impacts. The mountainous areas in the southwest of the state constitute regions of very low impacts across both data sets, while dense settlements along the foothill regions of both Sauerland and Eifel, such as Aachen and Wuppertal display elevated levels of impacts.

The cause-and-effect relationships translated into a quantitative representation via fuzzy logic are clearly determinable within our results. The maps in the decision tree (Figure 5.3) exemplify this using scenario data obtained from the STAR model. The resulting impacts can be traced back to the input values along the graph. In the cities of Cologne and Düsseldorf, for example, the low impacts can be clearly ascribed to the very low percentage of population ≥ 65 (0.2). While the potential UHI is very high, there are only very low numbers of especially sensitive age groups within both analysis periods. While all other input variables here are very high, the minor number of elderly as an especially sensitive age group significantly reduces impacts. Due to the γ-value, the results show a slightly augmented sensitivity and consequent impacts of 0.36 (low), thus taking into account the excess heat exposure through the UHI. Though the exposure is very high in this region, the low sensitivity determines the outcome. In the case of Dortmund, where a medium number of elderly population is present, the intense UHI leads to a high local sensitivity, again exemplifying the effect of the applied γ-value: without introducing this compensation, the UHI would not be accounted for and consequent impacts would be lower. In both of these examples the results correspond for both applied climate models. The example of Münster demonstrates that the area of sealed surfaces reduces the potential UHI, even though there is a high population density. With additional lower levels of population ≥ 65 the sensitivity as well as the impacts remain at a medium level with both climate models. In municipalities in the mountainous Sauerland region, for example in Winterberg, a very high proportion of sensitive elderly population coincides with very low values for all other variables, resulting in very low levels of impacts.

In several municipalities significant differences between the applied climate models can be observed in the results, as the models show different spatial characteristics (Fig.5.6). Gevelsberg, situated within the metropolitan region, shows the highest difference between the models: impacts are very high under the CCLM model with a value of 1 and medium under STAR assumptions with a value of 0.4. This is due to the different projections of HWD, with STAR projecting less HWD than CCLM under the A1B emission scenario. Similarly, for the city of Wuppertal, also situated in the metropolitan region, the number of HWD determine the level of impacts with very high levels for CCLM (0.81) and medium levels for STAR (0.45). The high percentage of sensitive age groups in the region of Rheine in the north of NRW entails medium levels of sensitivity. With input from the STAR model the results show medium impacts as there are significant numbers of HWD projected for the region. Results from the CCLM model, however, project a low number of HWD, consequently, the impacts are low.

4.1 Sensitivity analysis of model parameters and input data

Climate models present possible future developments on the basis of emission scenarios, which present possible future developments with no likelihood of occurrence ascribed (Nakićenović et al., 2000). The results of modeling runs depend on the underlying emission scenarios as well as the applied modeling technique (Gerstengarbe et al., 2004; Lautenschlager et al., 2009). The results of climate models present a range of possibilities. The climate models used in our study are based on the same emission scenario, yet the different modeling techniques lead to significant differences in the levels of HWD. Both regional models are currently considered equally valid.

The mean annual number of HWD simulated[2] with the CCLM model amounts to 3.4 for the baseline period, indicating one stronger heat wave per year on average. For the scenario period the mean number of HWD under CCLM amounts to 8 HWD per year. The observed data for the same period used within the STAR model shows an annual average of 1.2 HWD for the baseline period, amounting to one heat wave every three years and 5.8 HWD per year in the scenario period. Nevertheless, both models project a comparable increase in mean annual HWD of 4.6 (CCLM) and 4.5 (STAR). Thus, while the absolute numbers of HWD occurrence differ between the models the direction and magnitude of the projected changes are similar. These differences between climate models are also apparent in the results of our study. Overall levels of vulnerability are higher under CCLM assumptions, but the increases between baseline and scenario period are similar under both climate models (Figure 5.5).

Additionally, the spatial distribution of the projected increase differs between models (Figure 5.6). Within the CCLM model a visible regional differentiation is apparent with higher increases in the western part of the state and lower increases in the East. The STAR model on the other hand projects a more homogeneous increase across the state, which corresponds to the orography of the state. Both models agree that the strongest increase may occur in the Rhine valley; under CCLM this regional is increase more pronounced. In mountainous regions very slight increases in HWD are expected under both models, with lower increases under CCLM.

The influence of the variables on the overall results is critically determined by the membership functions. Figure 5.7 presents the normalised frequency distributions of the original data sets (a,c) and the respective membership functions (b,d) for the baseline values (a, b) and the scenario values (c, d).

The fuzzified data for those variables kept constant across both analysis periods show a U-distribution. Variables with projected values show left skewed (baseline) and right skewed (scenario) distributions, which correspond to a U-shape across both data sets. This

[2]For dynamical models such as CCLM data for the baseline period is modeled, while statistical models such as STAR are based on measured station data.

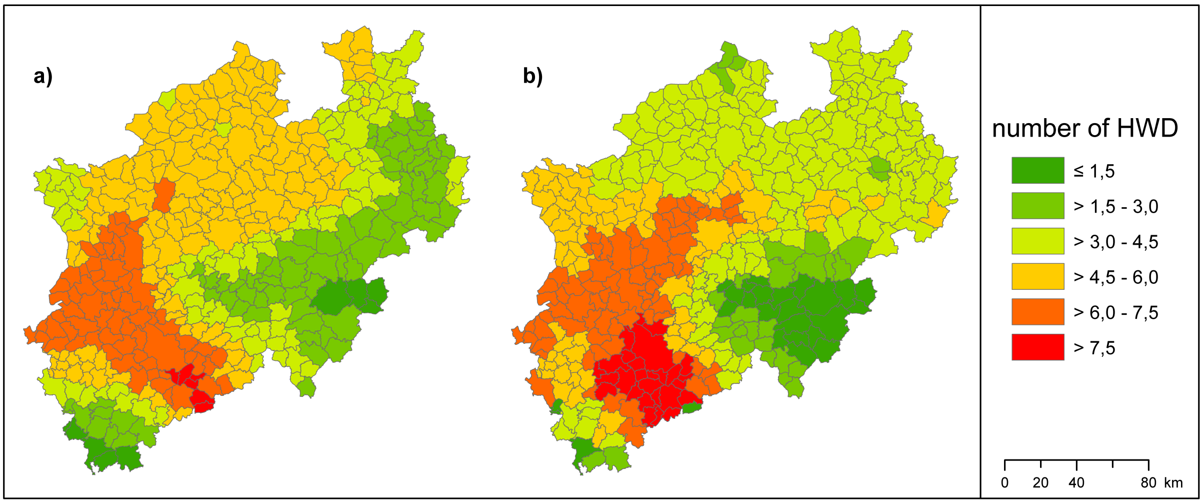

Figure 5.6: Increases in mean annual number of heatwave days between 1961-1990 and 2031-2060 for a) STAR and b) CCLM model results

means that most of the data is clearly ascribed to full (or respectively no) membership, while a smaller part is attributed to partial membership.

A higher proportion of the dynamic variables have full membership to the respective linguistic categories relative to the constant variables. This is founded in the cause-and-effect relationships identified in the impact chain, where a large increase in the dynamic variables augments the pressure on the system. Our fuzzified variables allow for the consideration of these ranges, as the threshold values for membership are motivated by the situation in the study region. Again, the differences between the climate models are visible: the frequency of full membership to $\mu\binom{\text{number of HWD}}{\text{high}}$ for scenario values is significantly higher for CCLM compared to STAR data.

We examined the sensitivity of the model results with respect to the input data values. For each variable at a time, the fuzzified data sets were set to minimum (0), then calculations were conducted as described in Section 3.3. To determine the impact of each variable, we assessed the resulting deviation from the original results. The variation of data sets to minimum clearly influences the analysis outcome, deriving from the application of the FUZZY_AND operator.

Those variables introduced into the decision tree at a later point have a higher impact on the overall outcome. The variables sealed surface area and population density have equal positions within the decision tree, therefore the model sensitivity is equal. A minimum value of population ≥ 65 has a much stronger influence on the result compared to the other variables. The highest deviations are observable resulting from variations in the variable number of HWD. Furthermore, in municipalities that display a high degree of vulnerability, results are most sensitive to changes in the input. The deviations from the original results are higher under CCLM assumptions across all varied input data sets.

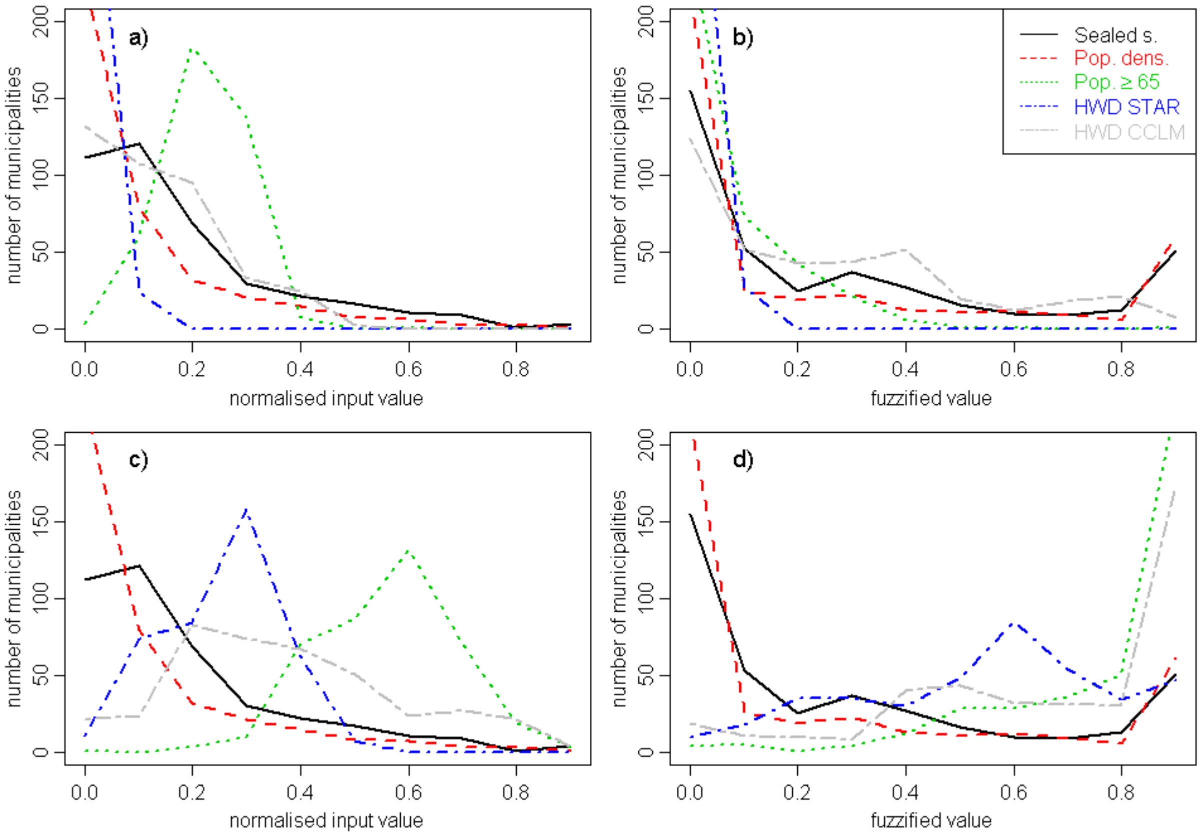

Figure 5.7: Frequency distributions of the normalised input variables (a,c) and the corresponding fuzzified variables (b,d) for values for the baseline period 1961-1990 (top) and the scenario period 2031-2060 (bottom)

This is due to higher numbers of HWD projected by this climate model (see Figure 5.6). The difference between the climate models is higher than the difference between variables under the assumptions of the same model.

The maps in Figure 5.8 depict which of the input variables has the strongest influence on the degree of impacts in each municipality for the scenario results.

In municipalities with high impacts the decisive factors differ between climate models. Where impacts are low, the decisive factors correspond. Generally the lower population determines the outcome with both models in rural areas. The lower percentage of population ≥ 65 determines the results in many urban areas, while in transition zones between urban and rural areas the sealed surfaces have a high influence on the results. The spatial differentiation of the occurrence of HWD is reflected in both maps. The STAR results project a spatially more homogenous distribution of HWD, however the overall numbers are lower than those of the CCLM model. Accordingly, a higher number of municipalities can be attributed to the decisive factor HWD within the STAR results (Fig. 5.8a). In the mountainous Sauerland region however, the projected number of HWD in the CCLM model is low (Fig. 5.8b) as this is the most decisive factor for the region. Again, the

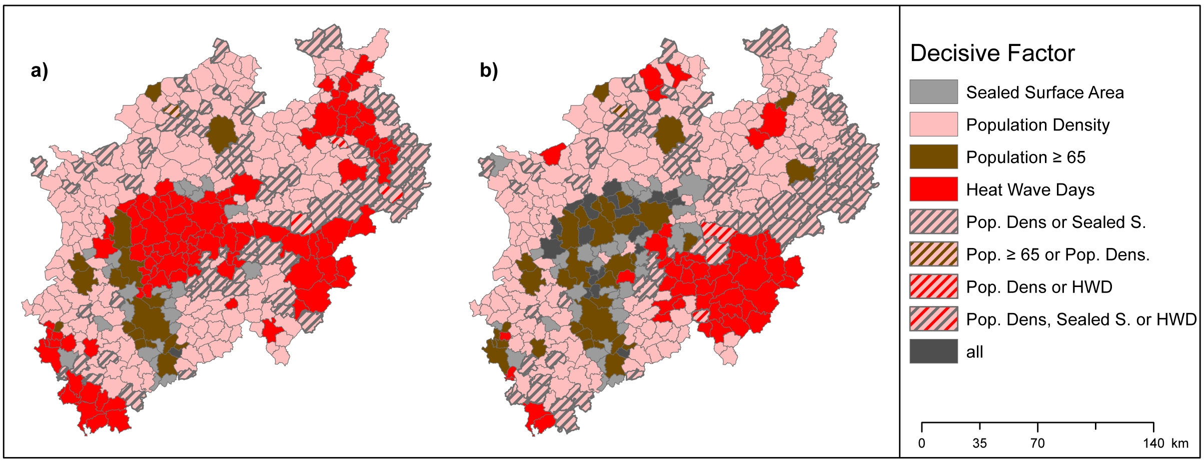

Figure 5.8: Factors most decisive for the resulting impacts in the scenario period for input data from the climate models a) STAR and b) CCLM

importance of the applied climate model becomes apparent.

5 Discussion

The clear cause-and-effect linkages implemented through the impact chain and represented through a fuzzy logic algorithm can depict a spatially explicit measure of impacts, while allowing for the identification of those factors where intervention may be most effective. Some general statements on the reasons for increasing impacts across the state can be drawn from the methodology. Additionally, specific constellations for the single municipalities can be traced through the methodology to derive suggestions for efficient adaptation possibilities.

We showed that the general spatial pattern of impacts is consistent across both climate models, with highest values in large metropolitan agglomerations and lowest values in the mountainous regions. These results are consistent with an analysis of heat related mortality in NRW for the hot summer in the year 2003 (Hertel et al., 2009; Hellmeier et al., 2007). For the medium sized city of Essen, located within the metropolitan region, a moderate increase in mortality was recorded. The rural and mountainous area of Siegen-Wittgenstein, however, exhibited no significant rise in mortality, even though the duration and intensity of excess heat was similar in the two regions. This discrepancy can be explained with a stronger UHI in the urban region of Essen.

The amount of HWD as defined by the applied climate model has a large effect on the mean impacts across the state and a smaller influence on the spatial variation. The main determinant of the spatial variation is the potential UHI. For determining hot-spot regions, the influence of sensitivity factors is higher than the influence of the applied climate models, as shown in the comparison of the climate models. This allows for a finer spatial resolution, which supports the focus of our analysis, namely the well-being of the population. Those municipalities, identified as highly or very highly impacted in the future under the assumptions of the STAR (55 municipalities) and CCLM model (78 municipalities), can be grouped by the input factor determining their impact value (Table 5.2). The resulting grouping differs for both models, especially regarding the factor heat waves, since these values are generally higher under CCLM, and thus a different decisive factor emerges (see also Fig.5.8). Nevertheless, for the other factors, the distribution of municipalities concerning these categories is quite similar under both models.

Further reduction of the input variable that mainly determines the result value will be most effective in reducing impacts. It is thus possible to identify measures that may most efficiently use available adaptation funds. We will exemplify this approach by means of selected municipalities (see Figure 5.1 for locations). A reduction in sealed surface could be advisable for municipalities like Kaarst or Bergisch Gladbach, where the sealed surface area is the decisive factor. It could thus be advisable to increase green spaces to reduce the urban heat island effect. This may hold true also for Löhne, where the population density determines the result and thus a reduction of the UHI may be especially beneficial. In cases like Münster where the number of elderly is the decisive factor, policies that ensure adequate education and awareness as well as access to medical services may be advisable.

Table 5.2: Number of municipalities with high and very high future impacts (value > 0.6) under the climate models STAR and CCLM grouped by the factor determining the result impact value (minimum) and indicating how the respective factors differ between models

	all factors	heat wave days	population aged 65 or older	population density	sealed surface area
No. municipalities (STAR)	1	34	9	3	9
Same factor under CCLM	1	1	9	3	9
Different factor under CCLM	0	33	0	0	0
Not highly vulnerable under CCLM	0	0	0	0	0
No. municipalities (CCLM)	20	6	24	11	17
Same factor under STAR	1	1	9	3	9
Different factor under STAR	17	0	10	3	3
Not highly vulnerable under STAR	2	5	5	5	5

Sankt Augustin, as one of the smallest municipalities in NRW shows the highest value for all factors under both models. The size of a municipality can influence the average values of population density and sealed surface area, increasing the resulting impacts in small urban municipalities. The spatial extent of the single municipalities influences our results as all input values are averages across these administrative units. Consequently, the spatial boundaries may not ideally reflect the distribution of land use types and distort the results. However, municipalities as administrative units are usually in the operational focus of decision makers and are thus the most suitable scale for our analysis.

While we found the spatial variation to be mainly determined by potential UHI, the number of HWD is of critical importance for levels of impacts in the single municipalities. As we showed in the analysis, the results are highly sensitive to the climate information. Available projections of future climates are subject to considerable uncertainty. They only present possible future developments with no likelihood of occurrence ascribed (Nakićenović et al., 2000). It is therefore important to base results on a range of climate models, when assessing possible future impacts. It would therefore be revealing to introduce further scenarios in addition to the A1B assumptions, especially so since currently this scenario proves to be very optimistic, considering current greenhouse gas emissions (Le Quéré et al., 2009). Projections for the variable population ≥ 65 are restricted up to the year 2030 while the climate data allows an analysis until 2060. We therefore assume constant values from 2030 onwards, which is rather conservative. Our assumption of a constant share of sealed surface area in the future is rather strong, yet no projections for this variable exist.

Our approach is helpful to identify climate change impact hot-spots where more detailed examination of local and regional vulnerability should be carried out. Local characteristics that are not captured at the present resolution of analysis may have a strong influence on the local and even individual susceptibility to suffer harm from heat waves. City-scale analysis of local characteristics, as presented by Mavrogianni et al. (2009) for example, can provide more detailed accounts in this context. Additionally, the issue of adaptive and coping capacities is difficult to capture at municipality resolution. Here, other methodologies, such as the analysis by Wolf et al. (2010) which assesses individual risk factors of sensitive population groups on city scale, can provide information on a lower scale. An analysis of this kind could complement our results for highly vulnerable municipalities to reveal detailed risk characteristics.

Our methodology can provide a basis for decision-makers on which to set priorities within the complex field of climate impacts. The structured approach through the impact chain as well as the aggregation methodology opens the possibility to infer from the outcome back to the main constituents of vulnerability. The reasoning thus works in both directions of the impact chain. It also offers ways of addressing similar problems in different regions in a consistent manner, thus opening ways of comparing and ranking impacts.

6 Conclusions

The presented assessment of spatially differentiated vulnerability of human health to heat waves within a standardized framework allows to identify local and regional hot spots in a comparable manner. The application of theoretically and empirically founded impact chains ensure contextual consistency. The use of fuzzy logic provides a means of dealing with uncertainty and inherently fuzzy thresholds or boundaries. In such a way health vulnerability has not yet been explained. As the study region covers spatially differentiated characteristics from dense urban to rural regions, as well as higher and lower elevation and gradients of heat exposure and could suitably exemplify the value of our approach: namely to present a spatially explicit depiction of differential impact severity in a reduced form model.

One major advantage of the applied method is the simplicity: we restrict the analysis to those input variables that are sufficient to describe vulnerability within the regional settings and necessary for the scale of analysis. To corroborate results it would be interesting to compare data of climate-related morbidity and mortality rates in the region with our results. The method presented is not limited to the analysis of health risks; it can be applied to other problem complexes, if one follows the clear-cut analytical framework as it was presented in this article. Future work will focus on refining the methodology to apply similar approaches to other areas affected by climate change. Although the presented method is not a model in a dynamical sense, the impact chain shows the relevant mechanism described in literature and thus provides an important diagnostic tool in the context of directed and efficient adaptation.

Summing up, the results obtained pave a promising road towards semi-quantitative description of climate change related risks. Decision makers facing a changing climate are often trapped in a no action situation, because comparable analysis are seldomly provided. By the simple approach presented here hot spots of future change are easily identified. Our approach thus clearly supports knowledge based decision making.

6
Synthesis

1 Summary of main findings

Inadequate livelihood conditions prevail in many regions of the world and climate change impacts often add on to existing development deficiencies, further reducing the adequacy of livelihoods and well-being. The chapters of this thesis present several approaches, which allow addressing the research gaps and challenges, which remain in the analysis of human livelihoods in this context. The following sections first summarize and discuss the main findings of the individual chapters in relation to the three research questions (RQ). Subsequently, the key contributions of this thesis to closing the research gaps and challenges (Chapter 1, Section 2) are reflected. Finally, this chapter gives a brief overview of the constraints of the presented analyses, it outlines further work and closes with some brief conclusions.

> **Research question I:** What are the main determinants and basic conditions needed for adequate livelihoods and human well-being?

Human well-being is a topic of high relevance for many aspects of global change research, however, a generally applicable approach to assess and measure the state of livelihood conditions in this context is not yet available. One important gap is the lack of a set of generic elements to describe human livelihoods well-being, which are valid at global scale and translatable into a measurable framework.

The analysis in this thesis identifies a total of 15 elements (Chapter 2, Table reftable:1:AHEAD), which allow for a systematic assessment of climate impacts on human livelihoods and well-being. To clarify the scope and goal for the purpose of this thesis, the analysis is framed to define elements that contribute to *Adequate Human livelihood conditions for wEll-being And Development (AHEAD)*. There are numerous studies devoted to the topic of livelihoods and well-being in general, which differ with regard to the terms used to describe the concept as well in the degree of detail and specification. Only few of these approaches are explicit about actual elements required for AHEAD fulfilment and a total of 11 approaches were applicable for the purpose of finding measurable elements for AHEAD (see Chapter 2, Section 2 and Appendix I, Table A-I.1). Nonetheless, where studies are explicit about specific elements, for the most part these are consistent across disciplines as well as approaches and it was possible to consolidate the relevant elements. These elements provide a systematic and generally valid basis, on which to assess the fulfilment and specific limitations to human livelihoods and well-being.

The literature review shows, that the scholarly debate of human well-being so far remains mostly conceptual. Where dimensions are explicitly identified, the focus is seldom on a potential translation into a measurable framework. This is evident with regard to subsistence needs, for instance: while these are consistently identified as relevant in the majority of approaches, single aspects, such as food or water, are usually not referred to individually or explicitly (Chapter 2, Figure 2.1). However, for a quantification such a differentiation into single elements is obviously relevant.

> **Research question II:** How can the main determinants of livelihoods and well-being be measured in a framework applicable in climate impact and sustainability research?

The first approach to quantify AHEAD (further referred to as A1) presented in Chapter 2 analyses associations and linkages between the identified elements. Systems thinking and the application of an influence matrix (Vester, 2007; Cole, 2006) provide an intuitive means of identifying relationships and feedback processes, which have been identified as a key feature of human-environmental systems (Liu et al., 2007). A1 focusses specifically on the properties of each element with regard to its relationships to other elements and the whole system. As exemplified with the example of water availability, changes in one element can have significant direct and indirect impacts on many other system components. Assessing changes within an interconnected setting can thus yield important additional information, allowing for a holistic understanding of the system. In the context of climate change, this approach gives important information on how impacts propagate through the system and affect human livelihoods and well-being directly as well as indirectly.

The second operationalisation of AHEAD in Chapter 3 (further referred to as A2) presents an approach to assess and quantify the fulfilment of AHEAD at global scale. Several challenges apply to such a quantification, including inconsistent units for example, but also the mathematical representation of vagueness and uncertainties associated with the identified elements, for example political stability. The use of fuzzy logic allows to translate such inherently fuzzy concepts into mathematical representations, by calculating the degree of membership to linguistic categories, in the case of this analysis with regard to the *adequacy* of conditions. A2 provides a means of quantifying the state of AHEAD conditions at specific points in time and space, also allowing to assess changes induced, as exemplified by assessing the impacts of water availability of overall livelihood conditions.

Briefly comparing the main characteristics of the two approaches, the system thinking approach (A1) focusses on the interlinkages within the AHEAD system, allowing to specifically address indirect effects of changes in one system component. The more static approach of A2 provides a quantification of AHEAD at specific points in time, providing a quantified representation individual limitations to livelihoods. In conjunction, the two perspectives can give indications of where interventions to improve livelihoods are most urgently needed and how such interventions may affect the system as a whole. Further details on the advantages as well as constraints of the methods will be discussed in Section 3.

Global overviews such as the ones presented in Chapters 2 and 3 can provide important information on general system properties. Sectoral analyses can then provide detailed information at regional to local scales, focussing on specific sectors, such as water availability or human health.

> **Research question III:** How can cause-and-effect retaining methodologies be developed, which allow for the identification of context specific limitations to livelihoods?

The representation of causal relationships through cause-and-effect retaining methods is an important aspect in assessments of human-environmental systems, in order to fully understand the main governing processes. A requirement for the development of such methods is a detailed qualitative understanding of the system under analysis. The initial focus of the analyses in Chapters 4 and 5 therefore lies on the systematic, qualitative outline of the relevant determinants which govern climate impacts on adequate water access as well as human health. For both studies, literature identifying the main determinants is abundant, but remains fragmented. The systematic synthesis of these aspects within a qualitative, conceptual outline provides a thorough understanding of the system, based on which specific livelihood limitations can be identified. Subsequently, each conceptual outline is translated into a mathematical representation, using fuzzy logic. As mentioned previously, by calculating the degree of membership to consistent linguistic categories, results become comparable between regions and across data. The process of fuzzification translates all input values unitless representation of the degree of membership to a defined linguistic concept, taking continuous truth values between 0 and 1. Based on logical clauses, the definition of context-specific aggregation rules within a directed graph allows retaining the identified cause-and-effect relationships within the final results, integrating complex knowledge.

In the aggregation of AHEAD elements in A2 (Chapter 3), for example, water as an absolute requirement for human subsistence is introduced to the analysis using a minimum operator to represent its property as an absolute limitation to meet human needs in situations of scarcity and this property is retained in the overall result. The differentiation of water using sectors and their specific requirements in Chapter 4 provides an important extension of existing approaches to measuring water availability, which often focus on single determinants of the availability of water only. By viewing all determining factors in conjunction, the approach provides sector-specific insights into the limitations of water adequacy and allows identifying the most limiting factor for each region and each sector. Chapter 5 shows how demographic, infrastructural as well as environmental factors can be combined in a meaningful way, exemplified in an assessment of heatwave impacts on human health. The chapter introduces the concept of impact chains for the assessment of climate impacts on relevant societal sectors, further elaborating the idea of retaining important cause-and-effect relationships between elements, when aggregating a range of variables into an integrated index. Similar to the assessment of water adequacy in Chapter 4, the most decisive factor for the results is identified. For each administrative unit of the study region, the intervention points for the most efficient reduction of potential vulnerability could be highlighted as a result.

2 Measuring livelihood limitations: key contributions of the thesis

The introductory Chapter 1, Section 2, outlined several open questions and challenges and stated three main objectives. The following paragraphs outline the key contributions that this thesis was able to make with regard to filling these existing research gaps.

Describing and measuring limitations to livelihoods and well-being

> To quantify limitations to livelihoods, a consistent set of elements to describe and measure human livelihoods and well-being is urgently needed.

Systematic approaches to assess livelihood conditions in the context of climate change in a comparable and transferable manner are urgently needed, however a consistent and systematic delineation and description of the requirements for adequate human livelihoods and well-being is so far unavailable. The systematic consolidation of elements to measure *Adequate Human livelihood conditions for wEll-being And Development (AHEAD)* presented in this thesis provides an important step forward in this regard, allowing to derive a disaggregated depiction of livelihood limitations.

The results show that in many regions, livelihoods are already limited today (Chapter 3). While a general divide between developed and developing countries, similar to the distribution of other measures of development such as the HDI (UNDP, 2013) for example is apparent, the distinction into the three domains of Subsistence, Infrastructure as well as Societal Structure provides important additional information. The analysis shows, that even in highly developed regions, livelihood conditions are often limited by societal factors and conditions are generally least adequate in the Societal Structure domain (Appendix II, Table A-II.2), underlining the need to include such aspects in a holistic approach to assessing livelihood limitations. The quantified representation of societal determinants in assessments of livelihood conditions so far remains the least sophisticated aspect and the inclusion and systematic representation of these aspects within AHEAD is an important contribution to the holistic representation of requirements for livelihoods and well-being (Chapter 2).

Following up on the assessment of AHEAD conditions and the relevance of water availability, the detailed assessment of water adequacy accounts for the fact, that most societal activities require water and each user has specific demands regarding quantity, quality as well as infrastructure (Chapter 4). The detailed analysis shows, that in many regions access and quality aspects are much more important rather than overall resource availability. Especially the impacts of environmental pollution and the associated threats to biodiversity limit water adequacy in both case studies. This underlines the fact, that development often leads to unsustainable side-effects, which may cause severe limitations to livelihood conditions and human well-being on the long-run.

Information of the potential impacts of climate change on human livelihoods are of high societal relevance. The findings on specific limitations to human livelihoods provided by the analyses in this thesis provide a basis, on which informed decisions can be made. The focus on determining the most decisive factors and sector-specific limitations are an important step towards establishing a scientifically sound knowledge base as well as deriving indications on how to most efficiently improve livelihood conditions.

Explanatory factors and cause-and-effect relationships

The translation of the multiple explanatory factors and cause-and-effect chains which govern human-environmental systems into meaningful and quantifiable representations requires methods, which allow retaining these causal relationships.

The initial implementation of AHEAD by means of an influence matrix (A1) is an important contribution to increase understanding of potential feedback effects, which exist in human-environmental systems (Liu et al., 2007). The analysis showed, for example, that societal elements of AHEAD, such as social cohesion and social protection, are highly active within the overall system and provide an important leverage points to improve livelihood conditions (Chapter 2, Figure 2.3). The relevance of societal aspects as intervention points, however, is usually not recognized in analyses of livelihood conditions or climate change adaptation studies. The approach provides a means of assessing, whether planned interventions will yield the expected results or potentially have negative consequences on other system components. For instance, if adaptation measures to counteract adverse consequence of climate change are implemented without sufficient knowledge of potential side-effects or the wider settings in which they take effect, such actions are potentially unsustainable and may even result in maladaptation (Barnett and O'Neill, 2010). By focussing on the main interactions and impact pathways, the approaches in this thesis can provide such information, directly focussing on potential repercussions of single actions on the overall system.

The fuzzy logic approach applied in the second implementation of AHEAD (A2), as well as in the detailed sectoral assessments, proved to be an important tool to further quantify and implement existing causal relationships, also taking into account the inherent vagueness associated with the quantification of AHEAD elements. As shown in Chapter 5, for instance, the severity of climate impacts on human health is determined by the concomitant occurrence of several factors with distinct causal relationships. Compared to other methods of aggregation, the use of a directed graph based on logical operators and taking into account context-specific vagueness allows translating important properties of the data into mathematical representations. The identification of decisive factors becomes possible through the development of cause-and-effect retaining methodologies and provides an important addition to existing studies of climate impacts, as it has clear focus on identifying individual limitations to livelihoods and provides a basis on which to efficiently improve conditions in a sustainable manner.

Bridging scales, combining data and addressing uncertainties

> Methods for the assessment of livelihood limitations in the context of climate change require addressing differing temporal and spatial scales, differences in measurements and units as well as handling uncertainties associated with climate models and scenarios.

This last set of methodological challenges is fundamental to any assessment of human-environmental interactions and the approaches presented in this thesis show some ways forward with regard to their consideration.

Depending on the scale and goal of analysis, different determinants are relevant to adequately represent processes. The assessments conducted in Chapters 3 and 4 show how, depending on context, goal and spatial scale, different levels of complexity can be taken into account to represent the adequacy of water resources. While specific determinants may vary according to the scale of analysis, the fuzzy logic methodology provides an objective approach, applicable to a variety of scales. Additionally, the available data to measure the elements contributing to AHEAD are derived with different methods and are measured in different units and scales. The representation of the degree of membership of all input factors to common a dimension, representing the adequacy of conditions, allows for the transferability of results between region as well as between scales, while allowing the combination of various data of different origins and units.

An important aspect of each analysis are the potential impacts of climate change. Climate change projections are subject to uncertainty, deriving from multiple sources (cascading uncertainties) (Schneider and Kuntz-Duriseti, 2002). While uncertainty is an integral part of scientific work and cannot be fully eliminated, the methods introduced in this thesis can contribute to determining their *relevance* with regard to a specific question. By viewing the range of potential future manifestations in a certain context, such as the adequacy of water resources for human livelihoods, it is possible to assess whether the result spread is relevant for human livelihoods. As the classification of results in Chapter 3 was able to show, for the majority of countries the uncertainty range is outside the critical boundaries for water security and human livelihoods. Similarly, Chapter 4 and 5 show, that modelling differences do not affect the results in the majority of regions, as other determinants of water adequacy and heatwave vulnerability are more decisive.

3 Constraints and outlook

While important contributions to advance the understanding of livelihood limitations could be made within this thesis, clearly there are constraints and further work could provide relevant additional information.

The initial identification of AHEAD elements, based on a comprehensive literature review, points at one important constraint: due to the variety of terms used to describe concepts of livelihoods and well-being, a systematic literature review confined to specific keywords proved difficult. While several analyses on the topic of livelihood requirements (e.g. O'Riordan, 2013; Littig and Griessler, 2005; Wisner et al., 2004) support the identified elements of AHEAD, nonetheless it is possible that additional elements of livelihoods requirements were not included, as these may be filed under a term not detected through the forward and backward searches within the literature.

Globally applicable approaches provide important information, however, the global and general scale also leads to simplifications, as important aspects, such as individual determinants of human well-being and livelihoods, cannot be taken into account. In the implementation of a system thinking approach (A1), this is especially apparent with regard to assessing relationships and associations between elements (see Annex II, Table A-II.3 for details), as it is difficult to identify relevant processes and define generally valid relationships from scientific literature alone. Relying on published sources, it became clear that there are regional variations in associations, and few relationships could be generalized. Additionally, many association exist, but have never been assessed scientifically or are not published. While the results clearly show that a focus on linkages between elements can uncover valuable additional information, the potential for its application at a global scale is limited, if linkages are based on scientific literature. A more detailed implementation of the approach, accounting for differences in temporal and spatial scale and drawing on local or regional knowledge would be an important extension. Here, for example expert-led participatory approaches could help in gaining the needed insights (Newell et al., 2005).

Fuzzy logic proved useful for the conducted analyses, however there are also some constraints to the method. In general, any type of assessment relies on assumptions, which may be subjective to some extent, and this is also true for the choice of membership functions and thresholds. Even though these are motivated by scientific findings, nonetheless other thresholds may also be justifiable, taking into account regional differences, for example. On a similar note, some indicators only have limited explanatory capacity at a global scale of assessment. The choice of the Falkenmark Index (Falkenmark, 1997; Falkenmark and Rockström, 2004) to represent adequate water availability (Chapter 3), for example, is the most widely used scientific indicator of water scarcity at global scale, however there is also awareness of its limitations. Sensitivity analyses provide an important means to assess how relevant a single threshold is for the overall analysis result and additional assessments of model sensitivity would be an important further step for the presented analyses.

Further work

The conducted analyses provided major insights and were able to address several research gaps, however several additional questions emerged during the analyses, which would provide interesting further analyses steps.

The assessments of climate impacts on livelihood conditions in various contexts showed the importance of assessing potential future changes in system determinants. In its present form, the approaches are mainly static assessments of the situations at specific points in time, with few dynamic elements. The incorporation of additional scenario values to include further dynamic aspects would be an important analysis step, as this would also allow to focus on the interlinkages between variables in more detail. While the linkages are generally addressed within the methodological approaches, further insights could be gained by investigating in detail how future changes in variables may interact. In this context, linking the results of additional detailed sectoral climate impact assessments relevant to AHEAD elements, as for example expected impacts on agricultural and energy production, would also yield important further information.

An additional field for the application of the AHEAD approach is the area of climate mitigation. In an initial assessment Reusser et al. (2013) show that many aspects of AHEAD are not associated with resource use and improving conditions with a focus on these elements would allow fulfilling livelihood conditions without additional resource use. A more detailed application of the approach in this direction, focussing on greenhouse gas emissions for example, could revoke the claim, that climate mitigation will diminish human well-being and development (Lorenzoni et al., 2007). Such a focus would provide an important contribution to the current debate on decoupling greenhouse gas emissions from human development (Costa et al., 2011; Jorgensen, 2014; Steinberger et al., 2012).

Especially in developing countries, climate change impacts add on to existing deficiencies and approaches such as the ones presented in this thesis provide a means to prioritize among limitations, while taking into account climate change impacts. The identification of decisive factors within the analysis allows for a direct identification of suitable intervention points to improve livelihoods and reduce specific limitations. While the present implementations of AHEAD quantify conditions at global scale, the approaches could easily be adapted to more local scales, also taking into account regional specificities with regard to elements. The sector-specific assessments at sub-national scale underline the importance of such more regionalised approaches, making visible regional to local variations in conditions. For instance, there are distinct differences between urban and rural areas, both in the assessments of water adequacy as well as human health. Further analyses at finer scales, drawing on local knowledge, could further improve the ability of the presented approaches to identify context-specific limitations.

Concluding remarks

The presented results make some important contributions towards linking aspects of global change to livelihood realities, as livelihood conditions can be quantified in a consistent framework. This framework is based on a synthesis of the most influential approaches to assessing livelihoods and human well-being and therefore reduces the existing problem of arbitrariness in the choice of elements to describe livelihoods. The systematic quantification of livelihood elements allows for an integrative assessment of the manifold consequences of climate change on human livelihoods. The focus on causal chains and the identification of specific limitations and decisive factors offer important information for informed decisions. They provide ways forward to improve the ability of impact assessments to yield applicable results and to improve understanding of processes at the human-environmental interface.

As shown in the selected examples, targeted and sector-specific methods at different levels of detail, complexity and scale are needed as blueprints and universally applicable methods are usually not feasible to address the full complexity of the topic of livelihood conditions and climate impacts. The development of a globally applicable, generic framework, linked to detailed assessments of specific livelihood limitations, is an important step forward in this regard, as it provides a means of comparing results within a common metric, while allowing to retain sector-specific information.

One of the biggest human challenges with regard to reaction to global climate change is the reconciliation of climate adaptation, climate mitigation as well as sustainable development. The reduction of poverty and a general increase in human well-being through further development therefore needs to be addressed within a context of reduced resource use, pollution and greenhouse gas emissions. A common metric such as the AHEAD approach to measuring livelihood conditions for human well-being, constitutes an important step towards jointly addressing the potentially diverging goals.

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Appendix I

Supplementary Material to Chapter 2: A systematic approach to assess human well-being demonstrated for impacts of climate change

Supplementary material to: *Lissner, Tabea K., Reusser, Dominik E., Lakes, Tobia, Kropp, Jürgen P. (2014): A systematic approach to assess human well-being demonstrated for impacts of climate change. Change and Adaptation in Socio-Ecological Systems. DOI: 10.2478/cass-2014-0010.*

List of Tables

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Table A-I.1: Theories and concepts included to identify relevant livelihood elements. The table corresponds to Figure 1, main text.

Theory	**Maslow's Theory of Human Motivation**	**Basic Human Needs Approach**	**Human Scale Development**	**Capability Approach**	**Human Security (HS)**	**Sustainable Livelihoods**
Sources	Maslow (1943)	McHale and McHale (1979); Doyal and Gough (1984); Weigel (1986)	Max-Neef (1992); Cruz et al. (2009)	Sen (1985); Anand et al. (2008); Gasper (2007); Nussbaum (2000)	Gasper (2005); UNDP (1994); King and Murray (2001)	Scoones (1998); Chambers and Conway (1991)
Main points	Independent categories of needs are related to distinct behavioral motives and associated with hierarchies of individual needs fulfillment (Pyramid of Needs)	Developed to tackle mass poverty, taking into account sustainability and broader progress, rather than focussing on increasing income alone	Ât'An influential operationalization of the Basic Needs Approach; distinction between needs, which are universal and finite, and satisfiers, which may differ across space and time	The resources (capabilities) a person has access to determine the possibilities to convert them into functionings. Capabilities express a persons freedom to put their aspirations into practice	A state of HS is achieved when poverty in any relevant domain of livelihood is absent.	Sustainable livelihoods can be achieved through access to a variety of livelihood resources in different contexts. Main requirements are listed, but may differ at other scales.

Table A-I.1: continued

Subsistence						
	• immediate physiological needs	• food, water	• subsistence	• life	• food • resource stocks as useful re-sources for livelihoods	
Shelter						
		• protective housing				
Health care						
		• physical health • health care • safe birth control		• bodily health • bodily in-tegrity	• health	• good health • physical ability
Education						
		• basic educa-tion	• understanding			• skills • knowledge

Table A-I.1: continued

Social protection	• safety		• protection		• social claims	
Economic stability		• economic security			• economic security	• capital base
Political Stability/Participation		• autonomy	• participation • freedom	• control over one's environment	• political security	
Security of person	• safety	• non-hazardous work environment • non-hazardous physical environment • physical security • security in childhood	• protection		• personal security	

Table A-I.1: continued

Social cohesion	• esteem/respect			• affiliation	• community	• network • social relations • associations • affiliations
Other aspects	• love (affection, belongingness) • self-actualization	• primary relationships	• affection • idleness/creation • identity	• emotions • senses, imagination, thought • play	• environmental security	

Table A-I.1: continued

Theory	**Quality of Life (QoL)**	**Subjective Well-Being (SWB)**	**Millennium Ecosystem Assessment**	**Dimensions of Poverty**	**Measurement of Economic Performance and Social Progress**
Sources	Cummins (1996); Costanza et al. (2007)	Diener et al. (1999), cited in Alkire (2002)	MEA (2005)	Narayan et al. (2000)	Stiglitz et al. (2009)
Main points	As a measurable approach QoL puts into practice a construct of (subjective) well-being	Four components make up the measure, namely pleasant effect, unpleasant effect, life satisfaction and domain satisfaction. The latter as measurable, external domains, are relevant for the present analysis.	With ecosystem services at the core of the MEA, the multiple linkages between aspects human well-being and ecosystems through supporting, provisioning, regulating, and cultural services are outlined.	Based on an extensive survey of poor people, dimensions of deprivation and poverty are identified, which reversely are those elements most needed to improve people's well-being.	The Commission's aim was to identify the limits of GDP as an indicator of economic performance and social progress and to consider additional information required for relevant indicators of social progress.

Table A-I.1: continued

Subsistence		• food	• Sufficient nutritious food • Access to clean air and water • Adequate Livelihoods	• Food	
Shelter		• housing	• Shelter	• Housing and shelter	
Health care	• health		• Strength • Feeling well	• Health	• Health
Education		• intelligence			• Education
Social protection	• safety			• Security in old age	

Table A-I.1: continued

Economic stability	• material well-being • productivity	• material resources • income	• Access to goods • Secure resource access	• Assets • Work	• Material living standards (income, consumption and wealth) • Security, of an economic as well as a physical nature
Political stability/Participation			• freedom of choice and action	• Freedom of choice and action	• Political voice and governance

Table A-I.1: continued

Security of person	• safety		• Personal safety • Security from disasters	• A physically safe and secure environment • Personal physical security	• Security, of an economic as well as a physical nature
Social cohesion	• community	• social life	• Social cohesion • Mutual respect	• Peace, harmony, good relations in the family/ community	• Social connections and relationships

Table A-I.1: continued

Other aspects					
	• emotional well-being • intimacy/friendship	• family • friendship • romantic relationship • self	• Ability to help others • opportunity what an individual values doing and being	• Appearances • Physical environment • Being able to care for, bring up, marry and settle children • Self-respect and dignity • Confidence in the future • Peace of mind • Happiness • Harmony (including a spiritual life and religious observance)	• Personal activities including work • Environment (present and future conditions)

Table A-I.2: The table lists the 15 identified elements relevant for AHEAD, following the order of Figure 1 (main text). Note that some elements are split up in order to enable measurability and three additional elements have been included. Column one and two list the operable element, its definition as well as its contribution to AHEAD. The last column lists the sources and synonyms used in different approaches.

Element	Relevance	Source and Synonym
Social cohesion	Social exclusion is associated with state fragility Marc et al. (2013) and increased rates of morbidity and mortality Howard and Bartram (2003); Stansfeld (2009).	In some form in most approaches, e.g. social cohesion MEA (2005), Community (security): UNDP (1994); Narayan et al. (2000); Cummins (1996).
Water availability	Water is a prerequisite for human survival and is essential for the provision of other human needs (e.g. food, energy production).	Doyal and Gough (1984); Narayan et al. (2000); MEA (2005); subsumed under subsistence needs in Max-Neef (1992); Maslow (1943)
Calorie availability	Malnutrition can have severe health effects; lack of calories can lead to starvation, lack of specific nutrients to specific diseases. Especially children are at risk of permanent damage if they receive insufficient food and nutrients FAO (2011); Brown (2002).	Diener and Biswas-Diener (2002); UNDP (1994); Narayan et al. (2000); MEA (2005); Doyal and Gough (1984); subsumed under subsistence needs in Max-Neef (1992); Maslow (1943)
Air quality	Sufficient air quality is a prerequisite for human health; many excess deaths are attributed to bad air quality WHO (2006); Wilkinson et al. (2007).	MEA (2005); Narayan et al. (2000); often mentioned with health or subsistence needs.
Health and health care	Health and the access to health care is important for human well-being and a prerequisite for any other activity.	Stiglitz et al. (2009); UNDP (1994); Cummins (1996); Nussbaum (2000); Doyal and Gough (1984); Scoones (1998); strength/feeling well MEA (2005); specific reference to health care infrastructure Narayan et al. (2000); Doyal and Gough (1984)

Table A-I.2: continued

Element	Relevance	Source and Synonym
Economic Stability	Secured basic economic resources (assets, secure livelihoods) are the basis for planning ahead and feeling secure about the future. Economic insecurity due to unemployment or unstable employment conditions pose health risks Howard and Bartram (2003).	Majority of approaches, e.g. economic security Stiglitz et al. (2009); UNDP (1994); Doyal and Gough (1984), capital base Scoones (1998), with some overlap to other elements, e.g. access to goods MEA (2005) and material resources Diener and Biswas-Diener (2002), which also refers to e.g. shelter, energy and food.
Security of Person	Personal security, e.g. feeling protected from direct violence, is important, as e.g. constant fear can lead to health problems Howard and Bartram (2003).	Aspects of (personal) security are mentioned in all approaches, e.g. personal security/safety UNDP (1994); MEA (2005) or safety Maslow (1943); Cummins (1996)
Political stability[1]	The institutional valuing of basic human rights is essential for secure living conditions. A functioning governance system can also support sustainable development Kabange (2013).	In some form in most approaches, but often subsumed under other categories e.g. governance/political voice Stiglitz et al. (2009), democracy/political security UNDP (1994).
Participation	Participation possibilities enhance the likelihood of sustainable development Morita and Zaelke (2005).	Max-Neef (1992); MEA (2005); Narayan et al. (2000), often subsumed under other categories, e.g. political voice Stiglitz et al. (2009) (see footnote 1)
Education	Understanding is a basic need to be able to participate in any important sphere of life and contributes to higher levels of participation and better health Lutz and Samir (2011). It is also an essential prerequisite for the possibility of adaptation and sustainable development.	Doyal and Gough (1984); UNDP (1994); Stiglitz et al. (2009); Scoones (1998)
Social protection	Access to support, if individuals lack the resources to support themselves is essential and can consist of institutional (state) schemes or be informal (communal). It provides an important aspect of security and support, should people not be able to support themselves.	(personal) security/safety MEA (2005); UNDP (1994); Narayan et al. (2000); Cummins (1996); (communal) protection Max-Neef (1992)

[1] The aspects of Political Stability and Participation are strongly interlinked and the approaches often have overlapping definitions. However, the identified elements are all discussed and distinguished as important.

Table A-I.2: continued

Element	Relevance	Source and Synonym
Shelter	Secure housing both affects the access to resources such as sanitation and water, but also provides protection from outside threats, security and dignity Brown (2003).	Max-Neef (1992); Diener et al. (1999); MEA (2005); Narayan et al. (2000)
Energy availability	Access to (affordable and clean) energy is a prerequisite for sustainable development, as energy is needed for most economic activities.	Narayan et al. (2000), further sources Pachauri (2004); AGECC (2010); Gaye (2008); Diffenbaugh (2012)
Communication	Access to information and communication technologies is essential for informed decisions and participation in life, especially in an increasingly technology-driven society Ogbomo and Ogbomo (2008).	Horner et al. (2010); Paliwala (2003).
Mobility	This refers to the physical ability to participate in society, including the economic, political and social life of the community Kenyon et al. (2002). Mobility is not only a means to an end, but has also been recognized as a need in itself Mokhtarian et al. (2001).	Mokhtarian et al. (2001); Bradbury (2006)

Table A-I.3: Interlinkages between elements of AHEAD, outlining the main characteristics of the directed relationships denoted with 1 in the influence diagram Figure 2.

	Effects of water availability on
Calorie availability	Food production is the largest water consumer; water is a critical constraint for food Falkenmark et al. (2009); Rockström et al. (2009); Khan and Hanjra (2009). Without precipitation for rain-fed agriculture and water resources for irrigation, crop growth is reduced.
Energy availability	Energy production relies on water for cooling, growing biomass for energy and water for hydro-power. Energy is the second-largest water consumer De Wever (2010).
Political stability	Levy et al. (2005) note that a correlation can be found between water scarcity and high intensity conflict, but not to low intensity conflicts within states. Reduced water availability has been shown to increase the potential for conflicts in some cases, however, this relationship is contested and cooperative water management is more frequent than (violent) conflict Scheffran and Battaglini (2010).
Economic stability	Adequate access to sufficient water reduces time spent to acquire water and generally raise health status, so more time can be spent on generating household income Meeks (2012); Larson et al. (2006).

Table A-I.3: continued

Education	Access to sufficient water may increase education, as time is freed to attend school Larson et al. (2006).
Effects of calorie availability on	
Political stability	Famine can lead to conflict and instability, but usually if other driving forces are also present, such as human rights violations or oppressive social inequalities Messer et al. (2001); Messer and Cohen (2004).
Education	Studies have shown that undernourished children have lower cognitive functioning and diminished capacity to learn and are prone to increased school absences Brown (2002). Though many studies support the link, Behrman (1996) argues that the causality is not proven, as there may be confounding factors. But since less availability will mean more time is needed to acquire food, less time will be spent on school Behrman (1996).
Effects of energy availability on	
Water availability	Making water available requires energy for moving, processing and transporting G8 (2001). In the U.S., 1.4% of total energy consumption goes to supplying cleaned water De Wever (2010), while numbers of up to 7 % have been cited globally Bazilian et al. (2011).
Calorie availability	On farm energy consumption accounts for 2-5% total energy in almost all countries, regardless of development status, e.g. for farm machinery, irrigation, fertilization and their production Khan and Hanjra (2009). Further energy is required for food processing Bazilian et al. (2011). Biofuel production may reduce calorie availability if agricultural land and commodities are used for biofuels.
Air quality	Energy production affects air quality at different levels. Especially the use of solid fuels for in-house energy generation results in indoor air pollution Desai et al. (2004). Depending on the prevailing type of energy production, outdoor air quality can also be negatively affected and total global numbers of premature deaths due to indoor and outdoor air pollution are high Wilkinson et al. (2007).
Education	Electrification of rural areas has shown to increase literacy significantly, as evenings can be used for studying Ranganathan and Ramanayya (1998). Further, tasks such as collecting fuel wood are replaced by energy, freeing time for study Kanagawa and Nakata (2007); Practical Action (2013).
Health care infrastructure	The provision of health care is dependant on energy availability for several purposes, e.g. specific treatments, adequate hygiene and continuous service (lighting) Practical Action (2013); G8 (2001).
Security of Person	The availability of electric street lights after dark can significantly improve security, especially of women Practical Action (2013).
Communication	Energy/electricity input is needed to access communication infrastructure, such as (mobile) phones and the internet, as well as information media, e.g. radio or television G8 (2001).
Mobility	Transport and travel for mobility rely on fuel and energy availability; the sector accounts for about 19% of energy use globally OECD/IEA (2009).
Effects of shelter on	

Table A-I.3: continued

Security of person	Shelter provides safety refuges from the dangers that exist outside - these may include violence but also health threats or weather impacts Brown (2003).
	Effects of social protection on
Security of Person	Social protection ensures that a person receives support of some kind, thus reducing direct threats to personal security, stemming from multiple sources which follow from insufficient funds to support needs. Causes of violence as a threat to personal security come from a variety of factors. Poverty, as well as inequality has been found to contribute. Social protection can ameliorate some of these circumstances WHO (2002a,b).
Social Cohesion	Poverty and income inequality can lead to a deterioration of social cohesion; social protection can reduce inequality and help to keep social cohesion intact Thorbecke (2002). Especially informal protection will increase cohesion.
Education	Having secured basic needs through social protection may increase education, as time is freed to attend school Larson et al. (2006).
	Effects of political stability on
Calorie availability	(Political) stability - or rather the absence of it in times of war and conflict - can lead to reduction of food production and changes in distribution patterns. Often also trade routes are interrupted, leading to food shortages and famine Messer et al. (2001); Messer and Cohen (2004).
Security of person	A lack of stability can increase the likelihood of conflicts and thus reduces personal security WHO (2002b,a).
	Effects of security of person on
Political stability	High levels of crime can lead to a higher potential for revolution and lower levels of democracy Thorbecke (2002).
	Effects of social cohesion on
Political stability	A breakdown of social cohesion could threaten democratic institutions Thorbecke (2002); Marc et al. (2013).
Security of person	Social cohesion has been found crucial to reduce state fragility and a lack of social cohesion can contribute to increased violence Marc et al. (2013).
Social protection	Strong social networks make more likely the transfer of assets (informal solidarity) Bradbury (2006).
	Effects of education on
Participation	Higher levels of education seem to increase likelihood for voting and other ways of civic participation. Understanding seems to be key to be able to access existing channels. It also increases the likelihood for citizens to inform themselves about candidates Milligan et al. (2004).
Economic stability	Education enhances job skills, or the ability to acquire them, and thus secures better economic positions to ensure (personal) economic stability. On a higher level, better educated personnel will ensure economic reliability and availability of skilled workers to keep productivity up Buechtemann and Soloff (1994).
	Effects of participation on

Table A-I.3: continued

Political stability	Higher rates of political participation are associated with lower inequality rates, which contribute to societal stability Mueller and Stratmann (2003); Thorbecke (2002).
Effects of mobility on	
Health care	Increased mobility has been found to significantly improve health status, due to better access to health care, as patients can more readily access the provided services Molesworth (2006).
Social cohesion	The access to transportation and mobility provides physical access to social networks Bradbury (2006); Kenyon et al. (2002).
Effects of communication on	
Social cohesion	Access to communication infrastructure and participation, as well as active communication within the community can promote social cohesion Paliwala (2003); Figueroa et al. (2002).
Participation	Access to information and to communication infrastructure enables and promotes participation and good governance Paliwala (2003); Horner et al. (2010).

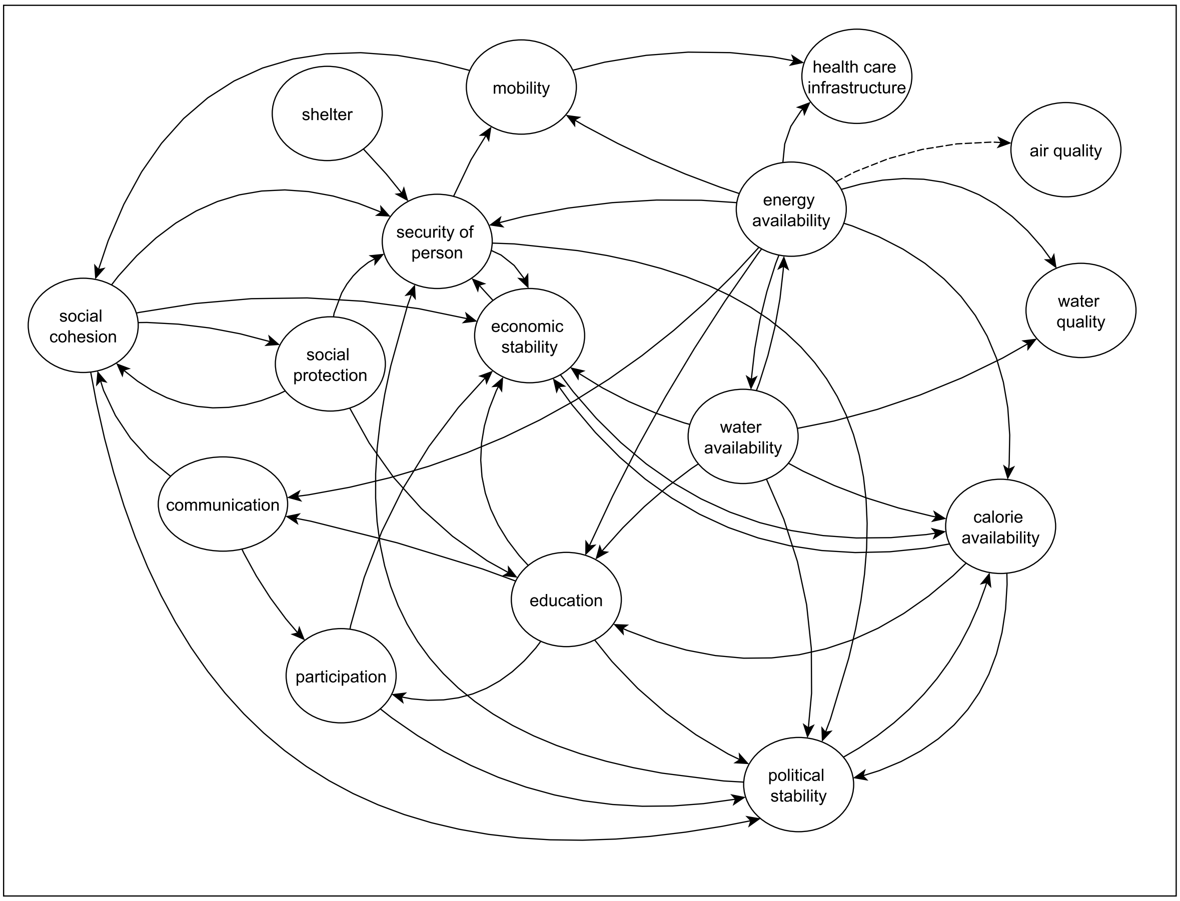

Figure A-I.1: Causal loop diagram of the AHEAD system. Arrows indicate linkages as denoted in Figure 2 and documented in Table A-I.3

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Appendix II

Supplementary Material to Chapter 3:
Climate impacts on human livelihoods: where uncertainty matters in projections of water availability

Supplementary material to: *Lissner, Tabea K., Reusser, Dominik E., Schewe, Jacob, Lakes, Tobia, Kropp, Jürgen P. (in press): Climate impacts on human livelihoods: where uncertainty matters in projections of water availability. Earth System Dynamics.*

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	very low	low	intermediate	high	very high
water	20	7	2	5	161
food	2	2	2	20	150
water.access	16	8	35	30	107
air	36	12	21	23	83
health	0	35	37	19	100
sanitation	13	20	22	22	119
energy	51	7	9	7	102
education	6	14	27	38	90
mobility	116	9	6	2	41
communication	34	35	38	51	37
social_protection	0	3	24	65	29
economic_stability	8	15	48	34	16
political_stability	4	5	14	26	72
security	5	8	23	31	54
social_inclusion	9	15	41	28	30
participation	32	29	33	16	13

Table A-II.2: Summary of the number of countries with lowest and highest adequacy values in the respective subindices.

	lowest adequacy	highest adequacy
subsistence	37	51
infrastructure	27	27
social structure	47	33

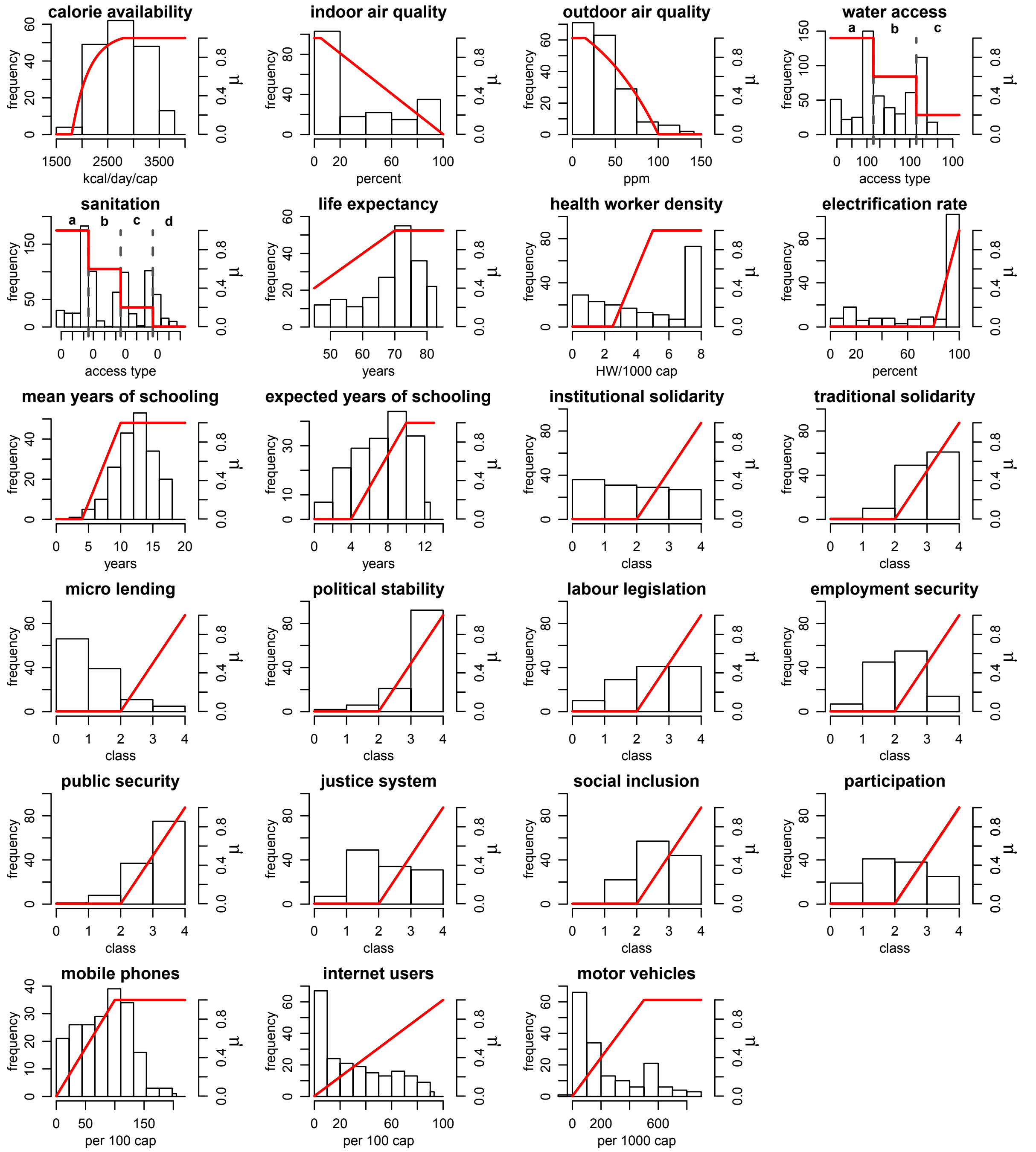

Figure A-II.1: Frequency distributions of the original input data and the membership function used for their fuzzification. For variable 'water access': a) piped on premises, b) other improved access, c) unimproved access. For variable 'sanitation': a) improved sanitation, b) shared facilities, c) other unimproved, d) open defecation.

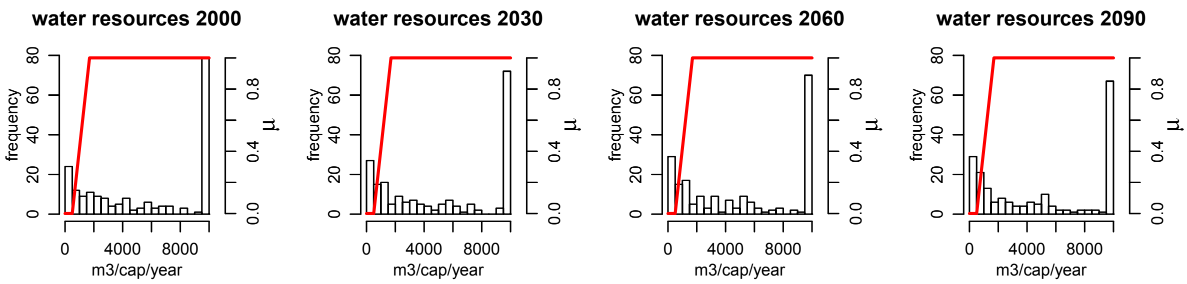

Figure A-II.2: Frequency distributions of the input data and membership functions for water resource availability. Values show the ensemble mean across all ISI-MIP climate and impact models for the four 30-year periods.